UNORTHODOX THOUGHTS ABOUT GRAIN-SIZE CRITERIA FOR ASSESSING SUFFUSION POTENTIAL

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SUMMARY

This extended abstract is a discussion about the eligibility, efficiency, significance and limitations of grain-size criteria to assess the vulnerability of well-graded granular soils against suffusion. Prevention of suffusion demands in a strong sense that independent of the power of the seepage all the grains remain members of the load carrying structure. A somewhat weaker definition allows a certain particle movement within a harmless scale, a local mobility, that will be stopped after the initiation of clogging. The author constitutes his perspective of grain-size criteria and introduces a very simple criterion based on Kézdy's separation approach as a tool of a first assessment, whether there is a threat in general or not. The paper comes to the final point, that despite laboratory tests and numerical simulation, the conditions in the field are governed by the inhomogeneity of the soil's structure. As this is the essential factor, the engineer of a dam has to judge the question during design, what would happen, if particle movement occurs.

INTRODUCTION

Internal erosion can occur in natural soils and earth structures in different modes and levels of risk. The phenomena are contact erosion, suffusion, liquefaction with backward erosion or chemical solution. The basic similarities are mobilization and transport of particles of the soil mass by a hydraulic or dynamic impact. While contact erosion or filtration appears at the interface between a finer and a coarser layer, suffusion acts in a unique soil mass, when the finer particles, embedded in the structure of a wide graded soil, are eroded by seepage.

To assess the sensitivity of non-cohesive soils to suffusion a number of criteria based on the shape of the grain-size distribution are used in engineering practice. Some criteria have a physical background, other are based on laboratory experiments and field observations [Semar et al., 2010].

This paper wants to look closer to the process of suffusion within a soil mass and attributes the phenomenon of suffusion to a process of internal contact erosion in the soil's structure. Finally, the applicability and limitations of grain-size criteria to assess the risk of suffusion are discussed under the aspect of unavoidable segregation and inhomogeneity.

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GRAIN-SIZE CRITERIA

CONTACT EROSION

In engineering practice the most commonly used Terzaghi criterion for protective filters guarantees a stable interface of a fine soil (base) and an adjacent coarser one (filter). Numerous tests carried out in our laboratory during the last decades have shown that even for well-graded homogeneous non cohesive soils the limit state relation is in the order

$$\frac{d_{15,f}}{d_{85,b}} \approx 9 \qquad (1)$$

where $d_{15,f}$ and $d_{85,b}$ are the grain-sizes of the filter and base corresponding to 15 % and 85 % finer by weight respectively.

Hence there is no sharp border between erosion and internal stability. Particle movement starts in a certain amount at a relation of 6 and increases up to a relation of 9 as a continuous washing through along preferential pathways, if the particles are not retained at any downstream barrier. For a given relation of the grain-sizes the depth of penetration to approach stability is proportional to the dimension of the transported grains. Measurements as well as numerical simulations have shown, that the network of pore paths within a filter allows movement of base particles only along very short distances at a relation $d_{15,f}$ / $d_{85,b} \leq 4$ [Vincens et al., 2015]. Therefore, we can expect cake filtration and internal stability due to a sieving effect.

Other criteria use other diameters of the grain-size distribution, d_{50} for example. But the author's opinion is, that rather for any shape of the grain-size distributions $d_{15,f}$ and $d_{85,b}$ are the best estimate of the controlling parameters, as the lower part of the gradation of the filter forms the structure with its spatial network of pore-constrictions, while the migrated largest base particles will accumulate at the interface and in the network of the pore paths. If there are enough coarse base particles, which are able to initiate clogging of pore paths the network will be constricted significantly. Stability will be achieved after a certain migration i. e. after a certain loss of base mass.

SUFFUSION

Suffusive soils are always well-graded, in most of the cases gap-graded, with a coefficient of uniformity $C_u > 20$. In a fundamental approach, there is a structure, called skeleton, consisting out of the particles which are in contact with each other and which transfers overburden pressure and external load. And there are embedded fines in the pore space of the skeleton, which are unloaded, and may be fragmented and fluidized, if there is a hydraulic or cyclic impact.

With this conception, the process of suffusion can be considered as a spatial contact erosion (filtration) where the skeleton's network of the pores acts as the filter while the embedded fine particles are considered as the base soil. The main difference between contact erosion at a distinct interface of two different layers and suffusion is (i) that, in contrary to an intact base layer, the embedded fines are mechanically unloaded and therefore, will be disarranged in case of seepage and (ii) that the embedded larger base particles are not distributed uniformly in the pore space of the skeleton due to the small mass of fill. Nevertheless, the physical process of blocking constrictions of pore paths pretending migration is similar, maybe in case of suffusion more randomly than at an interface with a greater area of contact. However, experimental investigation as well as numerical simulations have shown, that if retention along the pore paths is initiated the process of clogging increases rapidly.

With this geometrical model to analyze the potential of suffusion of a well-graded soil we have to consider four main parameters (1) the load bearing structure, i. e. the skeleton as a part of the entire grain-size distribution, (2) the porosity of the skeleton and its degree of saturation with embedded fines, (3) the diameter and mobility of the embedded fine particles and (4) the effective opening size of a possible pathway of erosion. In addition we have to assess the representativeness of these main parameters as homogeneity and unavoidable segregation of well-graded soils have a strong influence to the process.

For non-cohesive soils the separating diameter d_T of the portions belonging either to the skeleton or to the embedded fines can be determined easily by a laboratory test, according to Binner et al, 2010, the so-called Sequential Fill Test (SFT) [Salehi Sadaghiani & Witt, 2012]. Another approach is to find this essential parameter by numerical simulation as shown in [Winkler et al., 2014]. The accuracy of this technique is in the order of a factor of two, which is precise enough as in reality there is a fuzzy border between load bearing skeleton and embedded fines.

The saturation of the skeleton with fines may be derived from the same kind of test, but also by a mass-volume consideration. With the assumption of unique specific gravity and empirical values of porosity it can easily be shown that the saturation of the skeleton is complete, if the fines have an amount of about 28 to 30 % of the total mass. This structural boundary is reached, if the separating diameter is

$$d_T > d_{30} \qquad (2)$$

where d_{30} is related to the entire grain-size distribution.

If eq. (2) is fulfilled a bimodal structure consisting out of a skeleton and embedded unloaded fines is impossible. Under this condition, the soil’s structure consist out of an unique matrix of the fine portion, while the coarser grains are embedded. The pore space of the fines governs the physical behavior such as load transfer, strength, permeability, mobility. Suffusion cannot appear. All the reported suffusion tests carried out with such soils failed not by a suffusive particle transport but by liquefaction of the matrix due to a high excess pore pressure. But if the amount of embedded fines is under 30 % by mass ($d_T < d_{30}$), the vulnerability of particle transport increases slightly with a decreasing saturation of the skeletons pore space, as both the acting hydraulic load and the disarrangement of the fine particles will increase under constant hydraulic boundary conditions.

The third and fourth main parameter affect the geometrical balance of transport and retention, the verification, whether the mobile embedded particles can be retained at the constrictions of the skeleton’s network of pore paths. There are several methods to determine the kind and geometry of this network and the distribution of its constrictions [Vincens et al., 2015]. Based on a simple 3D percolation model Semar (2008) has shown, that there is no navigable pathway in the network for a particle with a diameter greater than 75 % of the spatial distribution of the constrictions. Therefore, the upper limit of the initial effective opening size of a 3D network of pores can be estimated by $d_{75,c}$ of the constriction size distribution.

To identify the potential of suffusion of well-graded granular soils for practical reasons we can go back to the well-established $d_{15,f} / d_{85,b}$ approach, considering d_{15} of the identified skeleton as filter and d_{85} of the embedded fines as base that should be protected. This idea goes back to a suggestion of Kézdy, 1969, to divide the grain-size distribution of a well-graded soil into two portions. The separated fine portion is considered as base, the coarser one has to act as the filter. To assess stability Terzaghi's criterion is suggested. This is justified as the separated gradation curves have are steeper with a lower coefficient of uniformity. The same consideration was proposed by Sherard, 1979. Chapuis, 1992, has shown that this criterion as well as the often recommended H/F criterion from Kenney and Lau, 1986, can also be expressed as an ultimate slope of the entire grain-size distribution. Based on this model of separation the author has defined a so-called *Self-Filtration-Index* I_{SF}, the relation of the relevant parameters of the separated parts of the grain-size distribution.

$$I_{SF}(d_T) = \frac{d_{15,\ coarser\ part}}{d_{85,\ finer\ part}} = \frac{d_{15,Skeleton}}{d_{85,embedded\ \ fines}} \tag{3}$$

The determination of both diameters does not require a true separation in a drawing. The projection of this diameters can be found at the entire unseparated grain-size distribution. The factor I_{SF} can be identified on this virgin gradation curve either as slope $m(d_T)$ in the virtual point of separation d_T or as any relation of the diameters of this curve with a increment of $\Delta y = 15\ \%$ finer by mass according eq. (6) such as d_{20}/d_5, d_{25}/d_{10} *or* $d_{30}/_{15}$.

$$m(d_T) = \frac{0{,}15}{\log I_{SF}} \tag{4}$$

$$I_{SF} = \frac{d_{y+15\%}}{d_y} \tag{5}$$

Introducing the empirical limit state relation for stability and instability mentioned above the criteria can be formulated

$$Stability \qquad I_{SF} \le 4 \;\; \rightarrow \;\; m \ge 0.193 \;\; \{=\} \;\; 19.3\,\%\ per\ decade \tag{6}$$

$$Instability \qquad I_{SF} \ge 9 \;\; \rightarrow \;\; m \le 0.157 \;\; \{=\} \;\; 15.7\,\%\ per\ decade \tag{7}$$

whereas the ultimate slope in a grain-size diagram can also be expressed as percentage per decade. Fig. 1 shows an example how to assess the internal stability based on the slope of the lower part of the grain-size distribution. From different investigations we know, that for this soil the particles with a diameter $d < 1.1\ mm$ are embedded in the skeleton and may be washed out.

This slope method can be used as a first approach to verify the vulnerability of a soil. If the slope of the gradation curve is steeper than m = 0.193 in the lower part up to d_{30}, there is no risk of suffusion. But if there is a flat tail or even a gap in the lower part and the slope is less than $m = 0.157$ over a range of 15 % mass finer by weight ($\Delta y = 15\ \%$), the soils tends to be suffusive. Drawing this limiting slope into the grain-size distribution gives a fast visual impression about the potential of suffusion. But comparing the slopes of eq (6) and (7) it can be shown, that the borderlines between stable and unstable are rather closely.

The amount of the particles that might be washed out if there is instability depend on the porosity, the hydraulic load and above all on the homogeneity of the soil's structure. The gravel shown in Fig. 1, a sediment from the middle reach of the river Rhine, was investigated intensely. The overall mobility of the fine grains which can be washed out is in the order of 3 %. Despite the soil is prone to suffusion, particle movement was stopped in the tested columns after a migration of about 30 cm due to clogging.

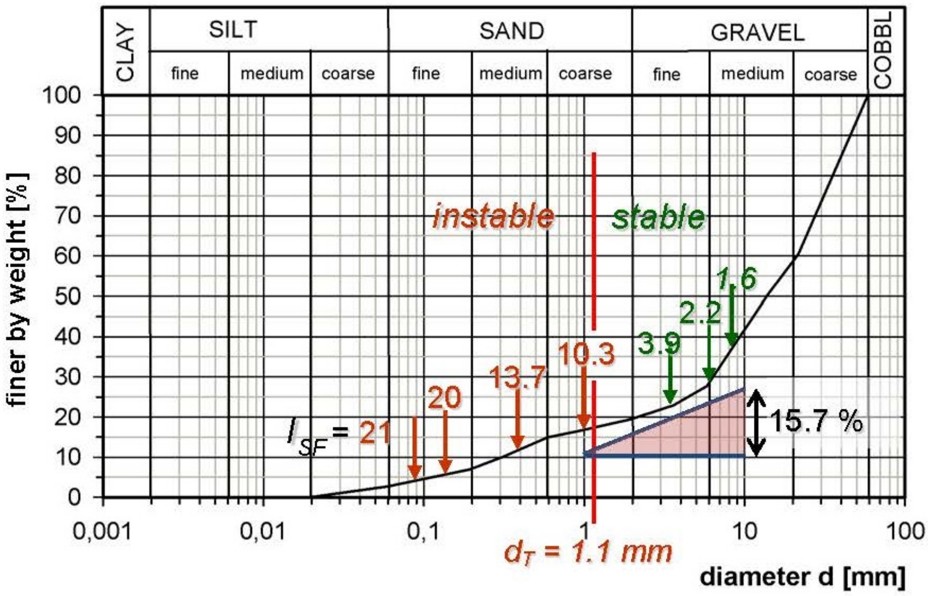

Figure 1. *Example of the assessment of internal stability with* I_{SF}

We have proved the efficiency of this simple I_{SF} grain-size criterion and have validated it with a lot of tests, published in literature, such as Wan &Fell, 2008, or Ni et al., 2015. In general the result of the assessment is in good accordance with published tests and with the assessment of other criteria. Hence, the meaning of the various criteria are different. Burenkowa's diagram is nothing than a fit of intense experimental investigations. Therefore, the test procedure has to be taken into account. The derivation and validation of the commonly used Kenney & Lau, 1986, H/F criterion is based on the Lubockov's ideal gradation curves, following a power function. If a soil fulfils this criterion, we are talking about an ideal gradation without predominant skeleton. All the grains are integrated into the structure, if this criterion is fulfilled and there is a homogeneous placing of the grains. In contrast, the I_{SF} criterion considers separation, assumes, that either a coarse grained skeleton is partially filled with unloaded fines, or the overall grain-size distribution is valid, but locally there is segregation. Under this condition, the criterion proves, whether the finer part is able to penetrate into the coarser one.

All grain-size criteria considered in this abstract are valid for granular soils without cohesion. Cohesive fines will strengthen a soil against suffusion dramatically. The geometrical considerations are still valid. However, we do not have to deal with grains but with aggregates. While even a smart seepage force is able to mobilize and transport grains of fine sand, we need a significantly higher seepage velocity in the soil to erode silt or clay particles. Nevertheless, following the ideal gradation according Kenney & Lau, particles cannot be transported. However, in a skeleton, partially saturated with cohesive soil, we might have long term effects of internal erosion, as a mechanically unloaded fine-grained soil tend to swell and takes water up to the liquid limit. Therefore single silty or clayey particles can be eroded and transported even at low gradients, without mobilizing the larger particles which are needed to initiate clogging.

CONCLUSIONS

Considered, the hydraulic load of a soil is great enough to erode and transport particles, internal stability and in particular, the occurrence of suffusion is a matter of kinematics in the micro-geometry on the particle-scale. The structure of the soil is the essential point. Therefore, the grain-size distribution has a major influence on this. There are a lot of criteria based on grain-size to assess the vulnerability of a soil against suffusion, and all of them are appropriate as we meet the specific assumptions and boundary conditions. The I_{SF} criterion, expressed as an ultimate slope of the gradation curve, is a reliable tool for a first assessment, as it shows whether suffusion might be a problem in general.

All the lessons we learned about internal instability and in particular about suffusion show that the assessment with a grain-size criterion is an adequate first step, the experiment in the laboratory goes deeper and delivers quantitative results about eroded mass in dependence of hydraulic load. But in engineering practice, we cannot build dams or other earthen structures with extremely well-graded soils without segregation. Therefore, the undefined fact of unavoidable inhomogeneity should be considered during design. There are different methods available, dealing with probability, spatial variation of the parameters, and their autocorrelation. Some experimental and theoretical approaches can be used to validate the degree of homogeneity in the field quantitatively [Salehi Sadaghiani, 2016]. But up to now, we do not have any acceptable target values, related to the threat of internal erosion. Therefore, we have (i) to mix up the soils during the earthworks in the field as good as possible, (ii) to accept unavoidable local particle movement, and (iii) to prevent a dramatic development of internal erosion by a conservative design with adequate downstream filters.

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