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ABSTRACT

The paper gives an evaluation of current practice to assess the vulnerability to suffusion. Therefore comparisons of different approaches concepts are summarized. Suffusion is characterized by the phenomena that the fines can move inside a soil skeleton. In practice the vulnerability to suffusion is evaluated in two steps. First the geometrical possibility of fine movement is analysed. If the fine particles are mobile the hydraulic conditions come into focus as triggering force. In this contribution the authors concentrate on the geometrical criteria used in current design practice. A comparison of limit state conditions and an evaluation of laboratory studies will be delivered. In addition new approaches based on statistical and stochastically methods are discussed.

Key words: suffusion, filter criteria, internal erosion, soil structure

INTRODUCTION

Internal erosion of soil structures is an essential problem for the long-term stability of earth structures impacted by seepage. One particular phenomenon of internal erosion, the displacement of fines in the grain skeleton, is called suffusion. When suffusion occurs than the permeability and the porosity will increase while the bulk density decreases. The consequences are a decrease of resistance against external load and settlement as well as significant change in the state of pore pressure [10].

In dependency of the location where suffusion might occur Ziems [34] distinguishes three types i. e. internal suffusion, external suffusion and contact suffusion (Figure 1). The mechanics of the process is very similar. The focus in this paper is located at the phenomena of internal suffusion. Good reviews to several kinds of internal erosion were published among others in [2, 19, 24, 25].

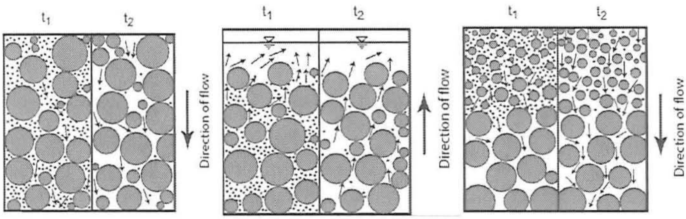


Figure 1: illustration of Suffusion by Ziems [34] for time steps t_1 and t_2.

Internal suffusion might be spatially restricted as a local phenomena where the fines will be trapped in dependency of particle size and hydrodynamic forces (colmatation). But suffusion can grow to a global wash out of fines from the grain skeleton. To exclude that internal suffusion of soils can occur it is necessary to satisfy two criteria. The sufficient criterion is the proof whether it is possible that fine material is able to pass through the smallest constrictions along the relevant pore path without clogging (geometrical criteria). The fundamental criterion is satisfied when it can be excluded that the hydrodynamic load in the pore structure provides a critical energy needed to mobilize and transport the fines (hydraulic criteria).

Geometrical suffusion criteria

The first researchers who concentrate on suffusive soils were motivated by creating mix filters in embankment dams instead of layered filters. Therefore they developed optimal mixture relationships. The concept was the creation of soils with minimum porosity based by experiences in the field of concrete technology. Such non suffusive soil mixtures were described e. g. by Pavčič, Talbot, Ochotin, Lupinskij (cited in [12]) and Sichardt [31]. With an absolute minimum of porosity two fundamental aspects are fulfilled,

- an uniform distribution of constriction sizes with a small mean value and therefore a minimum effective opening size
- a structure in which the majority of grains are fixed by a certain contact stress. This can bee assumed for homogeneous soils with a steady curved grain size distribution, a low porosity and therefore an uniform distribution of constriction sizes within the pore structure.

With this idealised packing providing a minimum porosity as propagated by Patrašev laboratory tests are carried out by Pavčič [22], Čištin [4] and Lubočkov [12, 13, 14, 15] developed empirical relationships (equation 1) to calculate perfect non-suffusive grain size distributions while taking into account the factor of uniformity C_U.

$$\frac{d_i}{d_{max}} = f(p_i, C_U) \qquad \text{respective} \qquad \frac{d_i}{d_{min}} = f(p_i, C_U) \tag{1}$$

p_i finer by weight of the grain diameter d_i

d_{max}, d_{min} maximum respectively minimum grain size diameter

In Europe the graphical approach by Lubočkov is used [12, 13, 14, 15] by comparing the normalized grain size distribution with empirical thresholds (Figure 2). Another empirical graphical approach is published by Burenkova [1] (Figure 3). This approach is valid for convex, concave and linear grain size distributions in semi-logarithmic scale. Gap graded grain size distributions can not be analysed.

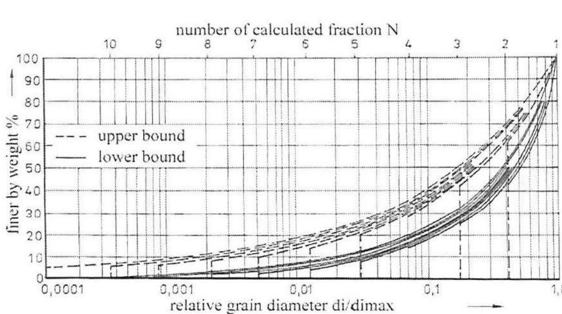
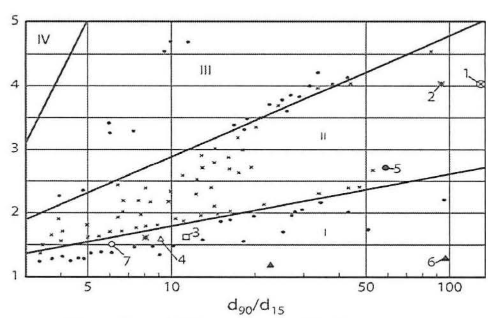


Figure 2: Upper and lower bound of non-suffusive soils by Lubočkov [13]



Zone I and III: suffusive

Zone II: non-suffusive

Zone IV: zone of artificial soils

Figure 3: Criterion of Burenkova [1]

Recognising the internal stability of a granular material results from an ability to prevent the loss of its own small particles due to disturbing influences such as seepage and vibration, Kenney and Lau [7] conducted a series of tests to define a threshold between stable and potentially unstable gradations. The base soils were well-graded sandy gravels and the filter materials a uniform medium or coarse gravel, or uniform distribution of coarse gravel and cobbles. Interpretation of the results based on a method of describing the shape of the grading curve and, therefore, is insensitive to grain size of the soil (see Figure 4).

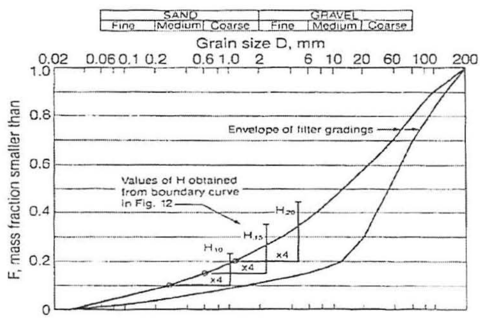


Figure 4: Shape analysis (after [7])

As illustrated, a discrete envelope of points (H) is established for selected intervals on the grading curve (F). If the grading curve lies below this envelope of points, over a designated portion of its finer end, then the gradation is deemed potentially unstable. The concept follows from that originally advanced by Lubočkov. The postulated boundary between stable and potentially unstable grading curves was firstly defined as $H/F = 1.3$ [7].

The experimental study of Kenney and Lau [7] generated significant discussion. Comments by Milligan [17], and additional work by Sherard and Dunnigan [30], led Kenney and Lau [8] to perform additional tests and redefine the postulated boundary between stable and potentially unstable grading curves as $H/F = 1$. Skempton and Brogan [32] report findings from piping tests on well graded and gap graded sandy gravels that broadly confirm the Kenney and Lau [8] criterion for internal stability. They found that there is an abrupt transition from stable to suffusive behaviour at about the limits defined by Kenney and Lau as well as those defined by Kezdi [9].

The above mentioned methods do not deliver sharp criteria in the classical engineering sense defining limit state conditions with a physical background. This empirical considerations give an idea whether a soil is vulnerable to be suffusive or not by analysing the heterogeneity and comparing the grain size distribution to thresholds.

The first geometric suffusion criterion based an physical considerations of the pore space was developed by Patrašev [21]. It is based on the idea that suffusion is impossible if the largest mobile particle d_s would not be able to pass through an equivalent pore size d_{po} (equation 2). This consideration introduces the fundamental approach, that there is a pore structure constituted by coarser fractions and a potentially mobile portion of grains, which are prone to erode.

$$d_s \geq d_{po} \qquad (2)$$

This kind of criteria is considered of several technical guidelines. The Russian guideline [20] denotes two criteria on this basis.

Alternative 1: Mobility of particles

$$\begin{aligned} &d_s \geq 0{,}77 \cdot d_{po} \text{ with} \\ &d_{po} = 0.455 \cdot (1 + 0.05 \cdot C_u) \cdot \sqrt[6]{C_u \cdot e \cdot d_{17}} \quad \text{for } C_u \leq 25 \\ &d_{po} = 0.16 \cdot \left(3 + \sqrt[3]{C_u \cdot \lg(C_u)}\right) \cdot \sqrt[6]{C_u \cdot e \cdot d_{17}} \quad \text{for } C_u > 25 \end{aligned} \qquad (3)$$

d_s largest suffusive grain size diameter

d_{po} effective opening size of the structure

d_{17} grain size diameter with 17% finer by weight

Alternative 2: Condition of suffusion

$$\frac{d_{3-5\%}}{d_{17}} \geq 0.32 \cdot (1 + 0.05 \cdot C_u) \cdot \sqrt[6]{C_u \cdot e} \qquad (4)$$

$d_{3-5\%}$ accepted loss from 3 to 5% finer by weight

In Germany the inequation 5 by Ziems [34] is used.

$$\begin{aligned} &d_{min} \geq 1.5 \cdot 0.6 \cdot 0.455 \cdot \sqrt[6]{C_u \cdot e \cdot d_{17}} \\ &\Leftrightarrow \frac{d_{0-3\%}}{d_{17}} \geq 0.41 \cdot \sqrt[6]{C_u \cdot e} \end{aligned}$$

In a study of filtration phenomena, Sherard et al. [28] concluded the filter design criterion, which Karl Terzaghi had formulated from his theoretical studies and companion special technical advising [5], is conservative, but not unduly so, for filters with a D_{15} greater than 1.0 mm. Alternative recommendations were made for finer filters suitable for base soils comprising fine-grained silts and clays [29]. Importantly, the authors noted that based on Terzaghi's criteria [33] the limit proposed by Kezdi [9] involves dividing the soil into a fine and coarse component, using select fines content on the grading curve. If the two components satisfy the filtration rule of Terzaghi [33], where $D_{15}/d_{85} < 4$, then the composite gradation will be self-filtering and therefore internally stable.

The Federal Waterways Engineering and Research Institute (BAW) in Germany as well recommend in a guideline [18] first to separate the grain size distribution into a finer and coarser part and to proof the stability with the geometrical filter criterion of Čištin/Ziems (Figure 5) afterwards. Steady grain size distributions, should be separate, at the inflection point. In case of gap graded grain size distributions it is reasonable to separate in the range of the gap (saddle point) [24]. The criterion of Čištin/Ziems was initially developed to analyse contact erosion phenomena. The geometrical criterion - i. e. no filtration - is satisfied if the relation $A50 = d_{50,II}/d_{50I}$ is less than the ultimate-relation $A_{50,ult}$ given at the y-axis of the chart in Figure 5. The index I indicates the base-material (fines), the index II is referred to the coarser material (filter).

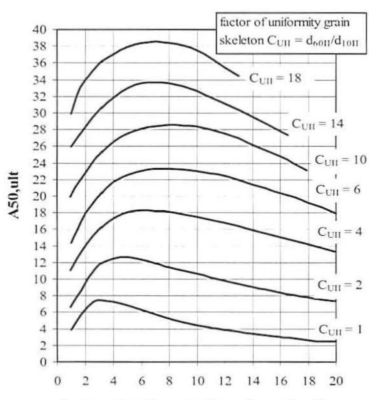


Figure 5: Criterion of Čištin/Ziems (cited in [2])

A unified approach combining the method of Kezdi and Kenney and Lau was established by Li and Fannin [11]. The common feature of both methods is the examination of the slope of the gradation curve over a discrete interval of its length [3]. The difference arises from the criterion used to establish the size of that interval: one approach uses a constant increment of percent finer by mass while, in contrast, the other uses a variable increment of grain size. More specifically, the D'_{15}/d'_{15} filter ratio of Kezdi [9] is calculated, by its very definition, over the constant increment of H = 15% at any point along the gradation curve. It implies a theoretical boundary to instability that is a linear relation on the semi-log plot of grain size. In contrast, the H/F stability index of Kenney and Lau [8] is calculated over the increment D to 4D, which increases in magnitude with progression along the gradation curve. It therefore implies a theoretical boundary to instability that is a non-linear relation and concave upwards in shape [11].

A plot of the respective Kezdi and Kenney and Lau boundaries, in F:H space, is given in Figure 6. At values of F > 15%, the method of Kenney and Lau defines a boundary to internal stability which locates above that of the Kezdi method. Conversely, the method of Kezdi defines a boundary above that of the Kenney and Lau method at F < 15%. The suggested limit values to stability of $D'_{15}/d'_{85} = 4$ and $H/F = 1$ yield a unique point on the gradation curve, where both criteria converge at $F \approx 15\%$. By inspection, the Kenney and Lau criterion is the more conservative of the two methods at F > 15%, while the Kezdi criterion is more conservative at F < 15%.

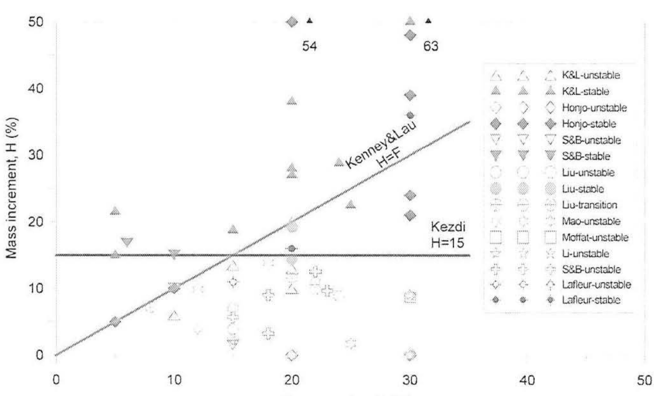


Figure 6: A unified approach for geometric analysis [11]

Merits of unifying some aspects of the two empirical methods are further examined in Figure 6. The data are those compiled by Li and Fannin [11] for 41 unstable soils and 22 stable soils. Inspection of the plot suggests the Kenney and Lau criterion of instability at $H/F < 1$ yields a more precise distinction between stable and unstable gradations at $F < 15\%$. In contrast, the Kezdi criterion yields a more precise distinction at $F > 15\%$. The resulting unified approach offers some improvements as a decision-support tool, and is currently being evaluated for adoption in engineering practice.

The above mentioned criteria allow permitting in advance which soils are definitely not vulnerable to suffusion. Therefore characteristically non-suffusive soils are [2, 25]:

- Soils with a factor of uniformity $C_U = d_{60}/d_{10} \approx 1$ (d_{60} and d_{10}: diameters of particles for which 60% or 10% are smaller by weight).
- Soils with a rather linear grain size distribution in semi-logarithmic scale with $C_U < 10$ irrespective of density index I_D.
- Non-uniform soils with $C_U > 10$ and $I_D > 0.6$
- Steady curved grain size distribution with $C_U < 8$ irrespective of I_D
- Non-uniform soils which are very close to the Fuller or Talbot grain size distribution. After Lubočkov [13] non-uniform soils with $I_D = 0.3$ till 0.6 and steady curved grain size distribution in border area of Figure 2.

The comparison of the different approaches shows that in general they are limited in their usability. Most of them are of empirical nature so that transferability has to be proofed. Mostly the limitation is the factor of uniformity or the gradation, because the empirical criteria are minimized to a range of soils. Also the empirical criteria do not distinguish between hydraulic and geometrical influences of particle transport. All aspects of transport and clogging phenomena are mixed up. Soils with slightly cohesive character can not be analysed with the common criteria, because the size of the eroded aggregates are unknown. Another disadvantage is that only the vulnerability to suffusion can be estimated or the largest suffusive particle diameter.

CURRENT RESEARCH

Two possibilities to derive better criteria are currently pursued, the empirical and theoretical way. The aim of the empirical way done for example by French project ERINOH and the European working group on internal erosion is the development of methods to a better prediction of the vulnerability to internal erosion. This includes in situ and laboratory studies. The methods regards primarily on the erodibility of soils.

Contrary the German research group "SUFFOS" supported by the German Research Foundation (DFG) are using a theoretical and modern approach to simulate transport and clogging processes inside a void structure, the so called percolation theory (above others [27]). This theory is a branch of the probability theory dealing with properties of random media. Determining the three-dimensional pore structure in advance is necessary to simulate the possibility of locally limited and global particle movement with the percolation theory adequately. In this sieve-analogy the governing soil structure is acting as a spatial sieve while the embedded fines are considered as a randomly distributed base material. The determination of the relevant pore structure is part of current research [6, 16, 27].

First general statements about local and global mobility of fines inside a grain structure can already be made with uncorrelated bond percolation models [27]. The constriction sizes of the grain skeleton are the controlling parameters for the fine movement possibility. A first approach can therefore be derived when using the constriction size distribution of the grain skeleton with Schulers' approach [26], which is the most promising at the moment. Other approaches to determine constriction size distributions and effective pore opening sizes are summarised in Reboul[23].

CONCLUSIONS

The comparison of the different approaches shows that they are limited in their usability. The limitations are the factor of uniformity. The empirical criteria are only valid for soils which are comparable to those analysed. Soils with cohesive fine fractions can not be analysed without uncertainties but resistance against erosion increases dramatically with increasing cohesion. Another disadvantage is that local effects and structural changes are completely neglected. Both can lead to significant settlements or to a negative impact on the hydrodynamic conditions [10].

At present the interest in further research is very high. Further work is required for example by Fannin to better establish the utility that may be derived from combining aspects of the two empirical methods, shown in Figure 6, and to account for relative conservatism in each of those methods. However, it appears:

I. The two methods of Kenney and Lau respectively Kezdi are predicated on a similar approach that involves quantifying the shape of the grain size distribution curve over a defined interval, but differ in how that interval is determined. The Kezdi method establishes it with reference to a constant increment of mass passing, whereas it is established by a variable increment in the Kenney and Lau method. This yields one point on the grain size curve where both methods converge to give the same index value, at $F \approx 15\%$.

II. Comparison indicates the filter ratio (D'_{15}/d'_{85}) of the Kezdi method is relatively more conservative for $F < 15\%$ and the stability index (H/F)min of the Kenney and Lau method is more conservative for $F > 15\%$.

A spatial sieve approach based on pore networks and percolation theory to simulate transport processes within the pore structure is part of the current research of the research group "SUFFOS". Anyway, all the approaches are based on the assumption that the soil is packed homogeneously. Hence the engineering practice shows that local segregation often is the focal point in suffusion. But up to now this effect cannot be taken into account in any safety consideration.

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REFERENCES

[1]V. V. Burenkova. Assessment of Suffosion in Non-Cohesive and Graded Soils. In J. Brauns, U. Schuler, and M. Heibaum, editors, *Filters in Geotechnical and Hydraulic Engineering on the First International Conference Geo-Filters*, Karlsruhe, 20.-22. Oktober, pages 357-367, Rotterdam, 1992, Balkema.

[2]K.-F. Busch, L. Luckner, and K. Tiemer. *Geohydraulik: Lehrbuch der Hydrogeologie*. Ferdinand Enke Verlag, 3rd edition

[3]R. P. Chapuis, Similarity of Internal Stability Criteria for Granular Soils. *Canadian Geotechnical Journal*, 29:711-713, 1992.

[4]J. Čištin. Zum Problem mechanischer Deformation nichtbindiger Lockergesteine durch die Sickerwassserströmung in Erddämmen. *Wasserwirtschaft Wassertechnik*, 2:45-49, 1967.

[5] R. J. Fannin. Karl Terzaghi: from theory to practice in geotechnical filter design. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 134:267.276, 2008

[6]U. Homberg, R. Binner, and S. Prohaska. Determining geometric grain structure from x-ray micro-tomograms of gradated soil. In K. J. Witt, editor, *Workshop Internal Erosion, volume 21* of *Schriftenreihe Geotechnik*, Witt, K. J., Nov. 2008

[7]T. C. Kenney and D. Lau, Internal Stability of Granular Filters. *Canadian Geotechnical Journal*, 22:32-43, 1985.

[8]T. C. Kenney and D. Lau. Internal Stability of Granular Filters: Reply. *Canadian Geotechnical Journal*, 23:420-423, 1986.

[9]A. Kezdi. *Soil physics – selected topics*. Elsevier Scientific Publishing Company, Amsterdam 1979.

[10] H. Leussink, T. G. Visweswaraiya, and H. Brendlin. Beitrag zur Kenntnis der bodenphysikalischen Eigenschaften von Mischböden. Veröffentlichung des Institutes für Bodenmechanik und Felsmechanik, Universität Karlsruhe, 1964, Heft 15.

[11] M. Li and R. J. Fannin. A comparison of two criteria for internal instability of granular soils. *Canadian Geotechnical Journal*, 45:1303-1309, 2008.

[12] E. A. Lubočkov. Nesuffozionnye nesvjaznye grunty. Technical Report 71, Izv. VNIIG, Leningrad, 1965.

[13] E. A. Lubočkov. Grafičeskie I analitičeskij sposoby opredelenija suffozionnych svojstv nesvjaznych gruntov. Technical Report 78, Izv. VNIIG, Leningrad, 1965

[14] E. A. Lubočkov. Calculation of the piping properties of cohesionless soils with the use of nonpiping analog. 2(3):233-237, Mar. 1968. Translation, original Gidrotechničeskoe stroitel'stvo.

[15] E. A. Lubočkov. The Calculation of Suffosion Properties of Non-Cohesive Soils when using the Non-Suffosion Analogue (russian). In *Internatinal Conference on Hydraulic Research*, pages 135-148, Brno, Czeckoslovakai, 1969.

[16] T. Mehlhorn, S. Prohaska, and V. Slowik. Modelling and analysis of particle and pore structures in soils. In K. J. Witt, editor, *Workshop Internal Erosion*, volume 21 of *Schriftenreihe Geotechnik*. Witt, K. J., Nov. 2008.

[17] V. Milligan. Internal stability of granular filters: Discussion. *Canadian Geotechnical Journal*, 23:414-418, 1986.

[18] MSD. Merkblatt: Standsicherheit von Dämmen an Bundeswasserstraßen. Technical Report, Bundesanstalt für Wasserbau, 2005.

[19] P. Muckenthaler. *Hydraulische Sicherheit von Staudämmen*. PhD thesis, TU München, 1989. Bericht Nr. 61.

[20] P-92-80. Instrukcija po proektirovaniju obratnyh fil'trov gidroehniceskih sooruzenij. VSN-02-65, 1981.

[21] A. N. Patrašev. Motedika podbora granulometričeskogo sostava obratnych fil'trov. Technical Report, Sbornik trudov Lengiprorečtransa, 1957.

[22] M. Pavčič. Sposob opredelenija nesuffozionych granulometričeskich sostavov grunta, 1961.

[23] N. Reboul. *Transport de particules dans les milieux granulaires. Application á l'érosin interne*. PhD thesis, L'école centrale de Lyon, Nov. 2008.

[24] U. Saucke. Nachweis der Sicherheit gegen innere Erosion für körnige Erdstoffe. *Geotechnik*: 4.-53, 2006.

[25] H. J. Schaef. Örtliche Standsicherheit (Suffusion und Erosion) bei Sickerwasserströmungen. Erläuterungen zum bodenmechanischen Arbeitsblatt 4.4 der ehemaligen Obersten Bergbehörde Leipzig. Technical Report, TU Bergakademie Freiberg, 1995. Veröffentlichungen des Institutes Geotechnik.

[26] U. Schuler. How to Deal with the Problem of Suffosion. In *Research and Development in the Field of Dams*, Sept. 1995. 7.-9. September.

[27] O. Semar and K. J. Witt. Percolation Theory – Phenomenological Approach to Describe Erosion Processes. In K. J. Witt, editor, *Workshop Internal Ersoion*, volume 21 of *Schriftenreihe Geotechnik*, Weimar. Nov. 2008.

[28] J. L. Sherard, L. P. Dunnigan and J. R. Talbot. Basic properties of sand and gravel filters. *Journal of Geotechnical Engineering-ASCE*, 110(6):684-700, 1984.

[29] J. L. Sherard, L. P. Dunnigan and J. R. Talbot. Filters for silts and clays. *Journal of Geotechnical Engineering-ASCE*, 110(6):701-718, 1984.

[30] J. L. Sherard and L. P. Dunnigan. Internal stability of granular filters: *Discussion. Canadian Geotechnical Journal*, 23:418-420, 1986.

[31] W. Sichardt. Kies und Sandfilter im Grund- und Wasserbau. *Die Bautechnik*, 29 (3/4), 1952.

[32] A. W. Skempton and J. M. Brogan. Experiments on piping in sandy gravels. *Géotechnique*, 44:449-460, 1994.

[33] K. Terzaghi. Soil mechanics: a new chapter in engineering science. *Journal of the Institution of Civil Engineering*. 12:106-141, 1939.

[34] J. Ziems. *Beitrag zur Kontakterosion nichtbindiger Erdstoffe*. PhD thesis, TU Dresden, 1969.