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INTERNAL SUFFOSION OF SOILS CRITERIA

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1. Introduction

Dams of water structures and tailings impoundments, bottom of excavated pits, soil medium under drainage, construction pits under lowering underground water etc. are stressed by seepage forces. Effecting volume load have therefore meaning for these constructions, because it can cause in different range movement of fine particles of porous medium and consequently results in a change of its structure and mechanical properties. Suffosion belongs primarily to undesirable phenomena caused by water flow in porous media. Internal suffusion in porous media occurs in case, that in appropriate volume of homogenous soil is a movement of fine particles in voids. This causes an increase in porosity and permeability of the effected material. If the wash out of larger particles (which forms skeleton of soil media) occurs, internal suffossion can cause settlement of soil. Prevention against internal suffosion can be performed by reducing hydraulic gradients and, in some cases, a proper compaction.

Suffosion is especially typical for loose materials, for gravely and sandy soils. In Fig. 1 there is a comparison of internally suffosive and internally non-suffosive soils. Formation of suffosion is affected by two assumptions: geometry of media and its hydrodynamic stress (i.e. geometric and hydraulic criterion of internal suffosion). Critical hydraulic gradient (or filtration velocity) is in most cases only a partial assumption for creation of filter failure. In order to indicate suffosion, also geometric criteria must be verified. The most common measure assessment of geometric criteria is grading curve of soil [1].

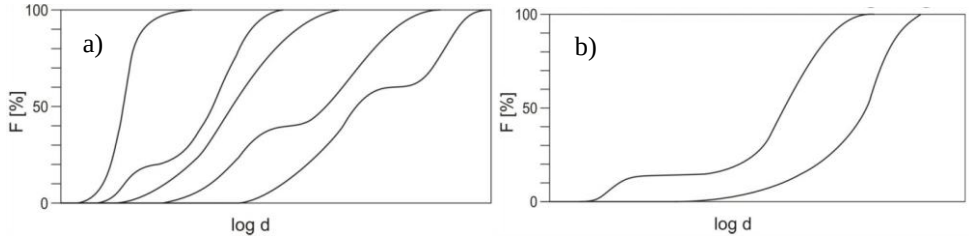

Fig. 1. a) Internally non-suffosive. b) Internally suffosive grading curves of soils [2].

2. Geometric criteria

According to Istomina and Čistín in [3], geometric criteria of internal suffosion are dependent on grading curve characteristics of soil, especially on uniformity coefficient:

- $C_u < 10$ – non-suffosive soils,
- $10 \leq C_u \leq 20$ – transition condition (soil can, but don´t have to be suffosive),
- $C_u > 20$ – suffosive soils.

For assessment of the possibility of internal suffosion in soil, the formula according to Instrukcija [3] is often used. Soil can be considered as non-suffosive whose composition suits the formula:

$$\frac{d_3}{d_{17}} \geq (0,32 + 0,016.C_u).\sqrt[6]{C_u}.\frac{n}{1-n} \tag{1}$$

According to Pavčič, maximum permissible diameter of seepage canals (voids) in soils is important, which can be expressed by the formula [1]:

$$d_{0\max} = 0,455.\sqrt[6]{C_u}.(1+0,05.C_u).\frac{n}{1-n}.d_{17} \tag{2}$$

For maximum grain diameter d_{suf} which can move due to suffusion, following applies:

$$d_{suf} = 0,77.d_{0\max} \tag{3}$$

If $d_{suf} < d_{\min}$ where $d_{\min}$ is the minimum diameter in soil, the soil is not susceptible to internal suffosion. If $d_{suf} > d_{\min}$, soil is internally suffosive, and then all the grains having a diameter less than d_{suf} can be wash out. If we accept the assumption, that some minimal wash out of finest particles is not risky for construction, the criteria for the internal suffosion can by edited. In case of dams and levees, washout of 3-5% particles from total volume of soil is usually admitted. Then the criterion of susceptibility of soil to internal suffosion is [1]:

$$d_{suf} \leq d_3 - d_5 \tag{4}$$

Simplified criteria according to Ziems is defined by condition: soil is not internally suffosive if have continuous grading curve and the following applies [2]:

$$C_u < 8 \tag{5}$$

Criteria according to Ziems (based on criteria according to Pavčič) also establish allowable voids diameter d_k [2]:

$$d_k = 0,455.\sqrt[6]{C_u}.\frac{n}{1-n}.d_{17} \tag{6}$$

According to Ziems, soil is resistant to internal suffosion if:

$$\frac{d_{\min}}{F_s.d_k} \geq 1,5 \tag{7}$$

The work [2] refers the methodology for estimation of internal suffosion susceptibility according to Kenney, Lau and Burenkova based on the following criteria and procedure:

Soil is not internally suffosive if: $H > 1,3.F$ (8)

Soil is internally suffosive if: $H < 1,0.F$ (9)

If soil is in transition zone: $1,0.F < H < 1,3.F$ (10)

In this case, the additional verification according to Burenkova is required.

F and *H* are obtained from grain size distribution curve of soil for any grains size *d* where *F* is from interval (0; *X*) (*X* is for soils with $C_u \leq 3$ equal to 30% and for soils with $C_u > 3$ equal to 20%) and $H = F_{4d} - F_d$ (Fig. 2; F_{4d} is fraction by weight of grains with diameter smaller than 4*d* [%]).

Assessment according to *H* vs. *F* criteria need to be done for several diameters *d* where *F* is from interval (0; *X*). Results are graphically interpreted on *H-F* diagram – Fig. 2.

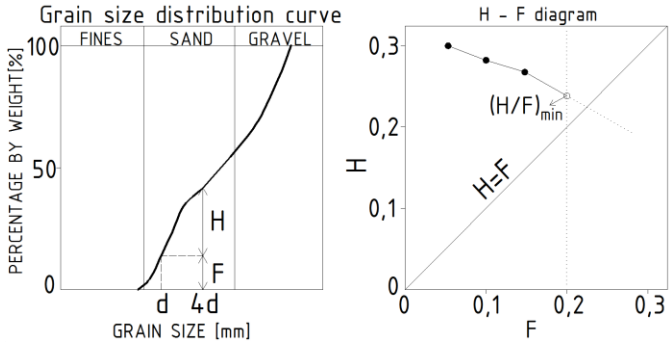

Fig. 2. Geometric criteria of internal suffusion according to Kenney and Lau [4].

According to Burenkova, internal suffosion susceptibility of soils depends on factors h' and h'', which are defined as follows [5]:

$$h' = d_{90} / d_{60}, h'' = d_{90} / d_{15} \tag{11}$$

By relationship between h' and log (h'') (Fig. 3), Burenkova defined boundaries between soils which are, and which are not internally suffosive. Area I and III represents soils which are internally suffosive, area II represents soils which are internally non-suffosive, and area IV represents a zone of artificial soils. Area II is approximately described by following relationship [5]:

$$0,76.\log(h'')+1 < h' < 1,86.(h'')+1 \tag{12}$$

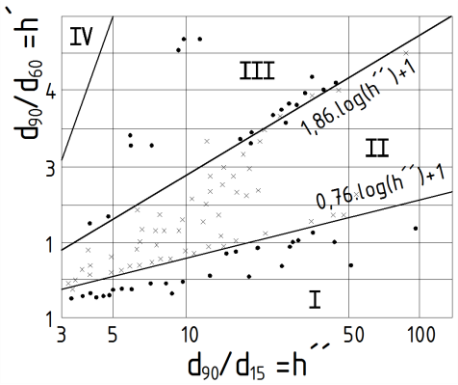

Fig. 3. Classification of internally suffosive and non-suffosive soils according to Burenkova [5].

Recommended procedure of internal suffosion assessment according [2] is presented schematically in Fig. 4.

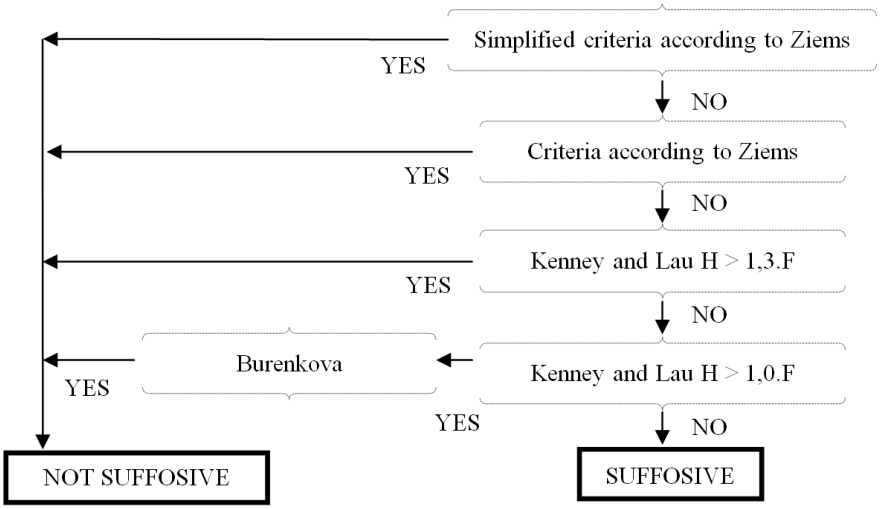

Fig. 4. Recommended procedure of internal suffosion assessment [2].

Work [6] shows formula according to Wan and Fell, who introduced geometric criteria of internal suffosion of soils, whose grading curves have bigger ratio between coarse and fine particle. Soil can be considered as non-suffosive when it meets the conditions:

$$\frac{30}{\log\left(\frac{d_{90}}{d_{60}}\right)} < 80 \quad \text{or} \tag{13}$$

$$\frac{30}{\log\left(\frac{d_{90}}{d_{60}}\right)} < 80 \text{ at once } \frac{15}{\log\left(\frac{d_{20}}{d_5}\right)} > 22 \tag{14}$$

3. Hydraulic criteria

In order to get particles into a motion, hydraulic criteria must be also verified, i.e. filtration velocity or hydraulic gradient exceed critical values v_{krit} or i_{krit}. According to Patrašev, critical hydraulic gradient for particles is smaller than d_{suf} (equation is valid for gravely soils):

$$i_{krit} = 0,6.\left(\frac{\gamma_s}{\gamma_w} - 1\right).\left[0,82 - 1,8.n + 0,0062.(C_u - 5)\right].\sin\left(30 + \frac{\upsilon}{8}\right).d_{suf}.\sqrt{\frac{n.g}{\nu.k_f}} \tag{15}$$

According to Terzaghi, limit equilibrium condition in vertical direction applies:

$$\gamma_{ef} = \gamma_w.i_{krit} = (1-n).(\gamma_s - \gamma_w) = \gamma_w.i_{krit} \rightarrow i_{krit} = \frac{(1-n).(\gamma_s - \gamma_w)}{\gamma_w} \tag{16}$$

Equations for calculation of critical filtration velocity are as follows [7]:

Ťavoda: $$v_{krit} = 0,041.\sqrt[3]{k_f} \tag{17}$$

Minc (d_{10} in [m]): $$v_{krit} = \frac{0,169}{\eta^{0,54}}\left[\frac{(2.C_u - 2).d_{10}}{\ln\frac{1,82.C_u - 0,8}{1,2 - 0,2.C_u}}\right]^{1,31} \tag{18}$$

Sichard: $$v_{krit} = \sqrt{k_f}\,/15 \tag{19}$$

Brno – VVÚVSH (d_{17} in [mm]): $$v_{krit} = \frac{n^3}{9.(1-n)}.\frac{(\gamma_s - \gamma_w).d_{17}}{18} \tag{20}$$

Vodgeo (d_{25} in [mm]): $$v_{krit} = 0,0125.n.\sqrt[3]{d_{25}} \tag{21}$$

4. Conclusion

Internal suffosion belongs to the most common damage of dams of water structures, tailings impoundments and soil mediums which are loaded by seepage forces. A wide range of criteria and factors of internal suffosion assessment gives considerable diversity of results. Therefore the right interpretation of assessment results is very important.

In case of geometric criteria of internal suffosion assessment, the results can be interpreted on the basis of the following facts and procedures:

- criteria according to Instrukcija, Pavčič and Ziems are conservative and strict,
- very good compliance and reliability gives criteria according to Istomina and *H-F* criteria – Kenney a Lau,
- assessment according to procedure in work [2]: Ziems → *H-F* criteria → Burenkova.

In case of hydraulic criteria, it is very important to determine the allowable hydraulic gradient and velocity. These values can be compared with the measured values, and, thereby, assess the risk of internal suffosion of soil.

Denotation of symbols

d_X - grain diameter corresponding on grading curve to X percentage of fraction by weight, [mm],
C_u - uniformity coefficient ($C_u = d_{60}/d_{10}$), [-],
n - porosity [-],
F_s - slip factor = 0,4, [-],
$d_{\min}$ - d_3, [mm],
F - fraction by weight of grains with diameter smaller than d, [%],
H - fraction by weight of grains with diameter between d and $4d$, [%],
γ_s - specific weight of soil, [N/m^3],
γ_w - unit weight of water, [N/m^3],
υ - the angle of deflection of the water flow direction from gravity direction, [°],
ν - kinematic viscosity of water, at temperature 10°C ($\nu = 1{,}307 \cdot 10^{-6}$ m^2/s), [m^2/s],
g - gravity acceleration, [m/s^2],
k_f - filtration coefficient, [m/s],
d_{suf} - maximum grain diameter which can be wash out by suffosion effect, [m],
γ_{ef} - effective weight of the soil, [N/m^3],
η - dynamic viscosity of water at temperature 10°C ($\eta = 1{,}307 \cdot 10^{-3}$ Pa·s), [Pa·s].

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Summary

Stress of soil medium by seepage force causes leaching of fine particles from soil skeleton, resulting in internal instability – internal suffosion. The paper is focused on search of internal suffosion criteria of soils and on the possibilities of interpreting the results of assesments according to several geometric and hydraulic criteria.