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Analysis of Soil Susceptibility to Internal Suffusion in Selected Sites for Impoundment Objects

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Abstract. In recent years, in Slovakia the construction of hydraulic structures focused on impoundment objects, which role is to utilize hydropower potential of watercourses by small hydropower plants. Construction and operation of the hydraulic structure requires to deal with issues connected with flow of seeping water and groundwater. One of the safety and reliability problems of hydraulic structures is to ensure the filtration stability of the geological environment. The most common problem with these structures is internal suffusion. Internal suffusion is defined as the transport of fine particles of soils in the porous environment due to hydrodynamic forces of seeping water. These processes can endanger the stability and serviceability of earth structures and solid structures of impoundment objects. A sufficient level of safety against internal suffusion can by ensured only by geological survey and analysis of the mechanical properties of the soils. Proposed paper is focused on internal suffusion. In our paper we analysed the geometric criteria of filtration stability for gravel soils for selected hydraulic structures according to the latest knowledge. By comparing several criteria and several samples of gravel soils with different mechanical properties we derived dependencies related to the filtration stability of gravel soils.

1. Introduction

For research purposes of filter stability criteria we focused our attention on the catchment area of the river Hron. It is the second longest river in Slovakia, with a length of 298 km, which flows into the Danube. We chose this catchment area because there are planned about 40 small hydropower plants and some of them were already built. The geological environment of the river basin is very diverse, but in most cases there can be found gravelly soils of various classes in the hydraulic structures subsoil. The basis for the examination of the filter stability criteria and supporting calculations were particularly grading curves of gravel soils and their filtration coefficients obtained from the reports of completed engineering-geological surveys. We had documentation of engineering-geological survey works from various locations of the hydraulic structures out of which 162 samples of gravel soil were available. [1, 2]

2. Filtration stability

There are several methods for assessing internal instability of soils. Basis of these methods are most often basic characteristics of soil and their grading curves. There must be fulfilled three conditions, geometric, hydraulic and spatial criteria to start moving of fine particles in porous media of the geological environment of hydraulic structures, i.e. suffusion or internal erosion [3]. Based on the geometric criterion we assess whether there can occur possible transport of fine-grain fraction in a

given porous medium, i.e. the shape, size and distribution of the grain and pores. Suffusive particles can start to move if they are loaded by sufficient water flow that gets them into motion. Thus there must be exceeded critical hydraulic gradient or critical values of filtration rate. Suffusive soil particles could be washed away from the environment only if there are available free spaces, where they can be stored or from which they can be further washed away. Such premises are for example drainage systems or sites which are formed by breaking of impermeable layer by uplift [4]. In our paper, we focused on geometric criteria mainly on the criterion according to Kenney & Lau and we compared it with the criteria used in our conditions.

2.1. Assessment according to Kenney & Lau

Kenney & Lau based their method on aspect of the structure and pore geometry [5]. They assume that a grain with the diameter d can move through a pore, which is formed by several grains with a diameter of 4d. To assess the filtration stability we can use a simplified graphical method that provides borders of suffusive, transient and non-suffusive zone. To assess suffusion it was necessary to construct the F-H curves (shape curves) of the grading curves of soil, which can be compared with the limit value for suffusive soils [5]. For construction of H-F curves we used characteristic grain diameters of d_3, d_{10}, d_{15} and d_{20}. Example illustration of that analysis result is depicted on figure 1.
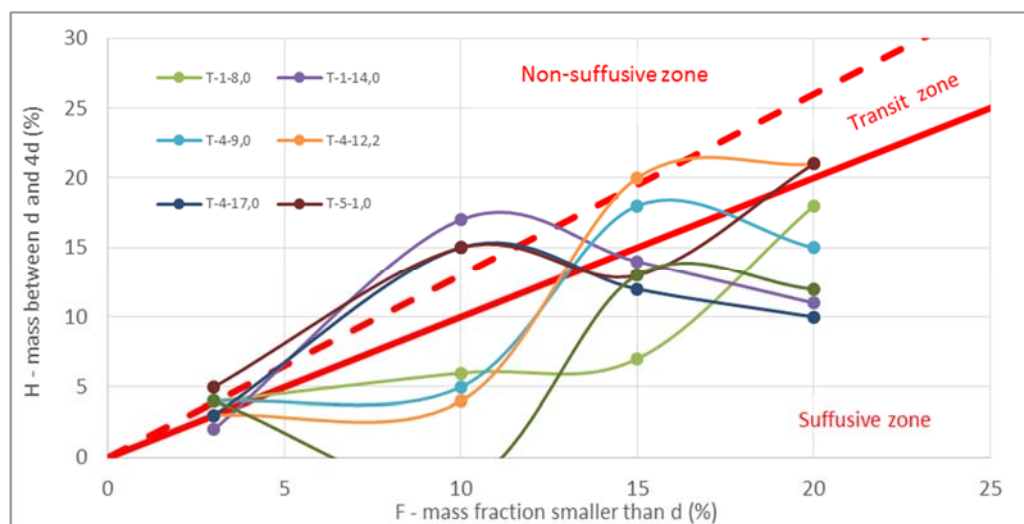

Figure 1. Example of determining suffusive soils according to Kenney & Lau method

In the same way, we analysed all 162 samples of gravel soils. Number of suffusive gravel soil samples was 118 (72.8%), 29 (17.9%) of the samples fell into the transit zone (there can but do not have to occur suffusion) and only 15 (9.2%) of the samples met the criteria for non-suffusive zone. Envelope curves of suffusive gravel soils samples classified as G1, G3 and G5 are depicted in figure 2. Soils of G4 (mouldy gravel) are omitted in figure 2 because of their little informative value (2 samples). It should be noted that the criteria for non-suffusive soils met only poorly graded gravels (G2 class). For this reason, we depicted their envelope curves of grading curves on a separate figure 3 in order to compare the suffusive and non-suffusive poorly graded gravels.
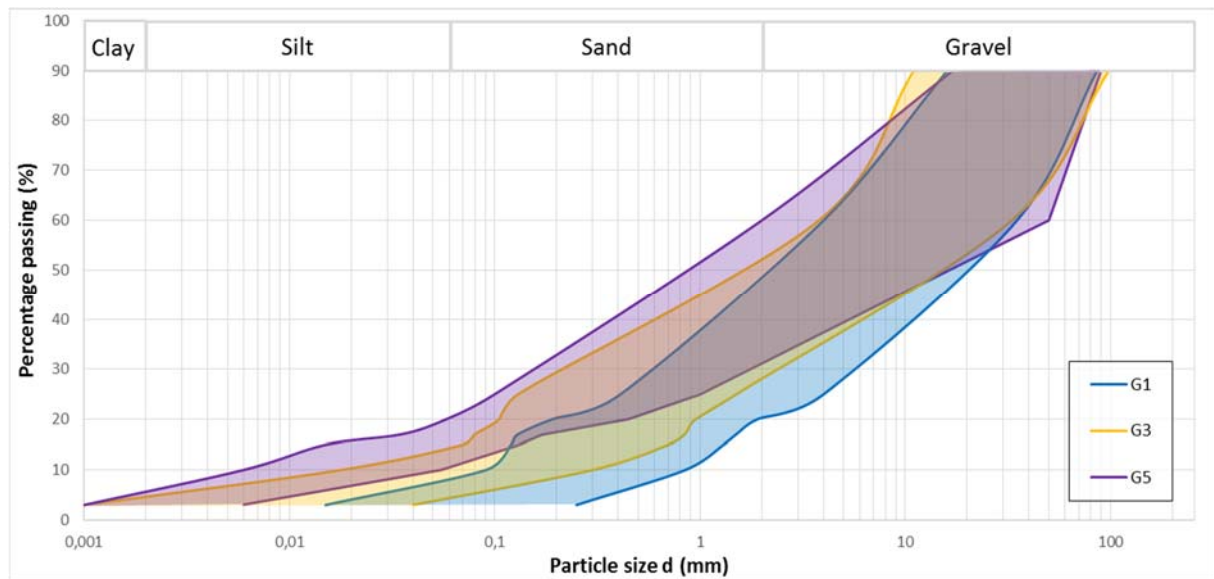
Figure 2. The envelope curves of suffusive and non-suffusive gravel soils classified as G1 (blue), G3 (orange), and G5 (violet)
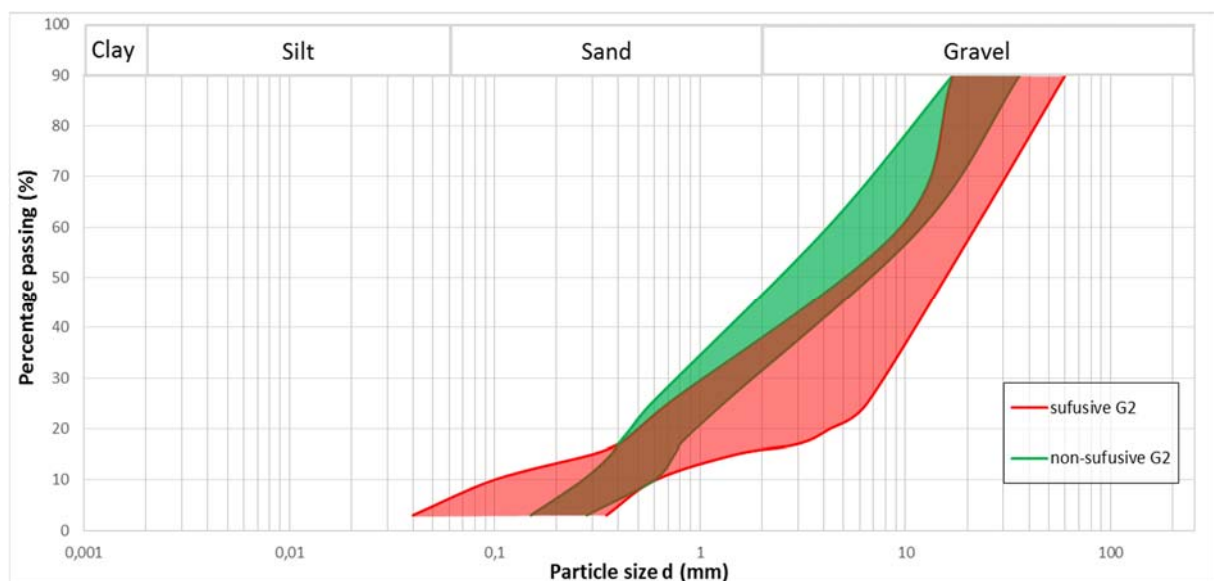

Figure 3. Comparison of the envelope curves of suffusive (red) and non-suffusive (green) samples of gravel soils classified as G2

From figure 3 it is evident that borders of suffusive and non-suffusive grading curves are not distinct because their envelope curves are intersecting. A characteristic feature of grading curves of suffusive soils is the lack of some soil fractions (stepping grading curve with horizontal or low-rising sections, respectively their grading curves are clearly convex). On the other hand grading curves of non-suffusive soils had approximately linear progressions. We analysed grading curves also by auxiliary values in soil classification namely uniformity coefficient, which characterizes the inclination of the central part of the grading curve and coefficient of gradation, which represents an approximate shape of the curve grading (Table 1).

Table 1. Uniformity coefficient and coefficient of gradation according to soil classification of examined samples

Soil classification	suffusive G1		suffusive G2		suffusive G3		suffusive G5		non-suffusive G2	
	C_U	C_c	C_U	C_c	C_U	C_c	C_U	C_c	C_U	C_c
average	53.4	0.57	53.8	2.34	171.5	0.61	830.3	0.59	15.0	0.5
median	45.1	0.49	48.8	0.41	109.5	0.34	588.9	0.50	15.0	0.4
maximum	112.9	0.94	130.0	23.21	1043.5	3.16	2533.3	1.34	20.0	1.4
minimum	14.5	0.16	20.4	0.13	44.4	0.03	200.0	0.15	8.9	0.1

According to the literature [6] soils with values of $C_c = 1$ až 3 a $C_U > 5$ are considered as well graded soils, therefore they should not be suffusive. Soils with values C_c outside of above mentioned interval belong to gap-graded soils, so it means that fine grain particles can be driven out under the influence of flowing groundwater. Only 11.5 % of well graded soils were accounted to the mentioned interval with only one sample was from the non-suffusive soils. The average value of the coefficient of gradation was significantly affected by the high value of some samples, so we chose median as decisive. However, from Table 1 it is clear that the coefficient of gradation median do not differ significantly between suffusive and non-suffusive soils. Therefore, consideration about non-suffusive soils in the literature is not in abeyance with the method according to Kenney & Lau. By comparing suffusive and non-suffusive soils of G2 class can be noticed significant differences in the medians and average values of uniformity coefficient. Suffusive soils reach significantly higher values than non-suffusive soils and their intervals vary considerably. Uniformity coefficient interval of suffusive soils is from 130.4 to 20.4 and for non-suffusive soils is from 20.0 to 8.9. Based on these findings we can conclude that the soil of class G2, which $C_U \leq 20$ and are within the range of non-suffusive envelope curves (figure 3 - green colour) will be assessed as non-suffusive according to Kenney & Lau methodology. Other gravel soils will be very likely assessed as suffusive.

2.2. Assessment according to other methods

We compared used Kenney & Lau method with other methods for assessing the filtration stability of soils. For comparison, we chose the method according to Instrukicja, based on Pavcic formula for calculation of the mean pore channel diameter [7]. It is assumed that the soil is internally stable if the soil does not lose more than 3 % of its volume due to flowing groundwater. The second comparative method was the method according to Istonima. Based on soil uniformity coefficient Istomina defined following criteria for a probable occurrence of internal suffusion [8]:

- $C_U < 10$ are non-suffusive soils,
- $10 \leq C_U \leq 20$ transition zone (there can but do not have to occur suffusion),
- $C_U > 20$ are suffusive soils.

The last comparing method was the method according to Zeims, which is based on theoretical considerations regarding the pore structure or the constriction distribution of the pore channels in the soil. It is also used modified formula according to Pavcic for calculation of mean pore channel diameter through which the fine particles can be driven out [9].

Table 2. Assessment results of gravel soils according to the above mentioned authors

number of samples	Instrukcija	Istomina	Zeims	Kennley & Lau
suffusive	152 (93.8 %)	140 (86.4 %)	129 (79.6 %)	118 (72.8 %)
non-suffusive	10 (6.2 %)	2 (1.2 %)	33 (2.4 %)	15 (9.3 %)
transit zone	-	20 (12.3 %)	-	29 (17.9 %)

By comparing criteria among each other it is clear that the Instrukcija method is the most conservative and hard from the point of view of the soil assessment to suffusion tendency because there was 93.8 % of the samples determined as suffusive. In most cases, if the sample was considered as suffusive by Instrukcija, then by other methods it was also assessed as suffusive or fell into the transit zone. According to Istomina there were less suffusive samples (86.4 %) but only 2 samples (1.2 %) were non-suffusive. Most of the samples fell into the transit zone (12.3%), where suffusion may or may not occur. The least suffusive samples (72.8%) were from an assessment according to Kenney & Lau, 9.3 % were non-suffusive and 17.9% occurred in the transit zone. Part of the analysis was also the compliance rate among the criteria used. Table 3 shows the absolute compliance rate with which the Kenney & Lau method coincides with other methods. Simultaneously the relative compliance rate is shown because in Kenney & Lau and Istomina methods transit zones are identified, where suffusion may or may not occur, but the Instrukcija and Zeims methods only identify whether the soil is suffusive or non-suffusive.

Table 3. Compliance comparison of the soil stability assessment according to the mentioned authors

Kenney & Lau	Instrukcija	Istomina	Zeims
compliance (%)	75.9	75.3	74.7
relative compliance (%)	79.0	82.7	82.1

Absolute compliance rate is about 75% among the used criteria. It is influenced by different approaches and methodology for assessing of the filtration stability by individual authors. If we take into account the transit zones, the relative compliance rate will increase about 6 % in average. Based on the number of suffusive soil samples and comparing the compliance rate of the mentioned methods we concluded that the criteria according to Instrukcija and Istomina belong to more conservative and strict and the criteria according to Zeims and Kenney & Lau are less strict in assessing the suffusive characteristic of soils.

3. Conclusion

In proposed paper we analysed filtration stability of the geological environment in the area of planned and even already built small hydropower plants in the river Hron basin. Attention was focused on geometric criteria. From analysis by different methods it was revealed that the majority of gravel soils are susceptible to suffusion, the movement of fine particles through pores is possible. By assessment of geometric criteria according to Kenney & Lau we obtained grading envelope curves of suffusive and non-suffusive soils. For all the analysed grading curves, we calculated the uniformity coefficient and coefficient of gradation. The theory about well graded soils, in which suffusion should not occur, did not comply with the geometric criteria according to Kenney & Lau. Among non-suffusive soils only soil samples of G2 and $C_U \leq 20$ were classified. This boundary corresponds with the criterion for the transition zone according to Istomina ($10 \leq C_U \leq 20$). A very good compliance was confirmed, because non-suffusive soils can exist in the transition zone. Other gravel soils were considered as suffusive. The results indicate that gravel soils of class G1, G3 and G5 will very likely be vulnerable to suffusion in the Hron river basin. By comparing criteria of several authors, we concluded that the

criteria according to Instrukcija and Istomina are more conservative and strict and the criteria according to Zeims and Kenney & Lau are less strict in assessing the suffusive characteristic of soils. Compliance rate among the criteria used is approximately 75%. The difference can be attributed to an approach and methodology of individual authors for assessing the filtration stability. Findings from the analysis of 162 samples of gravel soils in the basin of the River Hron pointed out that it is appropriate to use several methods for assessing filtration stability of soils. By using only one method we do not obtain a sufficient level of reliability about suffusive characteristics of soils in the given area.

References
[1]   G. Šikula, J. Škvarka, and J. Filo, "MVE - TEKOV pozorovacie sondy". Ekogeos Zakladanie s.r.o., Bratislava, 2013
[2]   G. Šikula, J. Škvarka, and M. Takáčová, "Záverečná správa z orientačného IGP". Ekogeos Zakladanie s.r.o., Bratislava, 2009
[3]   M. Lukáč, E. Bednárová, Navrhovanie a prevádzka vodných stavieb : Sypané priehrady a hrádze. Jaga group, s. r. o., Bratislava, 2006
[4]   J. Říha, Ochranné hráze na vodních tocích. Grada Publishing, a.s, Praha, 2010
[5]   C.F. Wan, R. Fell, "Experimental investigation of internal instability of soils in embankment dams and their foundations", New South Wales 2004,
[6]   L. Lamboj, Z. Štepánek, MECHANIKA ZEMIN A ZAKLADÁNÍ STAVEB. Nakladatelství ČVUT, Praha, 2008
[7]   Bundesanstalt für Wasserbau, BAW Code of Practice : Internal Erosion (MMB) BAW Codes of Practice and Guidelines Publisher, Karlsruhe, 2013
[8]   Istomina, Filtracionnaja ustojčivosť gruntov, Moskva, 1957
[9]   A.L. Goldin, L.N. Rasskazov, Design of earth dams. Balkema, Rotterdam.