https://doi.org/10.1051/e3sconf/202336802015

# Recent developments in design criteria for granular and geotextile filters

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**Abstract.** Granular and geotextile filters are commonly provided in several hydrological infrastructures to limit soil erosion and allow unimpeded water seepage. The success of a filter depends on forming a bridging structure, which is governed by the grain size distribution of soil and the constriction size distribution of filter. Currently, the retention requirement is satisfied considering representative grain and opening size, whereas the hydraulic conductivity requirement is satisfied considering empirical factors for avoiding excessive clogging. In this paper, the design criteria for granular and geotextile filters are reviewed, and improved design criteria are presented. A probabilistic retention criterion is developed, considering the grain size and constriction size as random variables. The influence of filter thickness is incorporated into the criterion by considering the number of constrictions in a filtration path. A hydraulic conductivity criterion is developed theoretically based on governing flow equations and the expected partial clogging of geotextiles. The limit states for the developed criteria are evaluated based on the wide range of experimental data. The developed design criteria are applicable to granular and nonwoven geotextiles, which offers an improvement in design compared to the existing criteria in practice.

## 1 Introduction

Seepage through the porous earth structure might cause instability due to the migration of soil grains. Filters are provided to control the excessive erosion while allowing the unimpeded seepage of water. In Civil Engineering, the filters are classified as granular and geotextile filters. Filters are required to satisfy two conflicting requirements of retention and hydraulic conductivity. The retention and hydraulic conductivity criteria are required to be satisfied such that erosion is limited and the flow is unimpeded, respectively.

The filtration phenomenon is primarily governed by Grain Size Distribution (GSD) of soil and Constriction Size Distribution (CSD) of a filter. The filter works on the principle of self-filtration, as shown in Fig. 1, where the coarser grains are retained by the filter, and the coarser grains retain the finer grains by forming a stable skeleton structure, also commonly known as bridging structure. The grain and constriction sizes belong to the category of random variables of aleatory uncertainty. Consequently, the filters must be designed considering the probability that a random-sized grain infiltrates into random constriction size.

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However, in practice, the retention requirement is satisfied considering the representative grain size and opening size of filter.
This paper aims to present improved design criteria for retention and hydraulic conductivity requirement for granular and geotextile filters. The specific objectives are: (1) To review the existing design criteria for granular and geotextile filters, (2) To develop a probabilistic assessment criterion for the retention requirement, and (3) To develop a hydraulic conductivity criterion based on the governing flow equations and expected partial clogging of filter.

# 2 Existing filter criteria

## 2.1 Granular Filters

Granular filters are required to satisfy three requirements of retention, hydraulic conductivity, and internal stability. Internal stability refers to the ability of a coarser fraction of soil to prevent the loss of fine fraction caused by seepage flow. The details of the requirements are given below.

### *2.1.1 Retention criterion*

Terzaghi [1] provided a rational criterion for retaining soil with uniformly graded granular filters. The retention criterion (Eq. 1) states that $d_{15}^{f}/5$ , a representative opening size of the granular filter must be small enough to retain grain size greater than $d_{85}$ of the soil and grain sizes less than $d_{85}^{s}$ will be retained after forming a stable skeleton structure [2].

$$d_{15}^{gf} \le 5d_{85}^{s} \tag{1}$$

where $d_x$ is the grain size at $x$% passing with superscript $gf$ and $s$ denoting granular filter and soil.

Several studies [3,4,5] recommended different coefficients and grain sizes for non-uniform filter gradation. The development of the CSD estimation has improved the empirical retention criteria. Indraratna et al. [6] proposed a retention criterion based on the controlling constriction size. Srivastava and Sivakumar Babu [7] presented analytical expressions for the safety of retention and hydraulic conductivity. Nguyen et al. [8] improved Indraratna and Vafai's [9] analytical solution based on energy conservation to solve the Navier Stoke equation.

### *2.1.2 Hydraulic conductivity criterion*

Terzaghi [1] provided the hydraulic conductivity criterion (Eq. 2), which states that the hydraulic conductivity of granular filters should be approximately 25 times more than the hydraulic conductivity of soil; hydraulic conductivity is directly proportional to the $d_{15}^{2}$ .

$$d_{15}^{gf} \ge 5d_{15}^{s} \tag{2}$$

The hydraulic conductivity requirement includes no excess pore pressure development at the soil-filter interface, and the flow rate should be greater than the flow rate in the soil without a filter. Giroud [2] has reported that excess pore pressure is not developed if the condition given in Eq. (3) is satisfied, while the flow rate is not reduced (below 10%) if the condition shown in Eq. (4) is satisfied.

$$k_{s}^{gf} \ge i_{s}k_{s}^{s} \tag{3}$$

$$k_s^{gf} \geq 25k_s^s \tag{4}$$

where $k_s^s$ and $k_s^{gf}$ are saturated hydraulic conductivity of soil and granular filter, respectively.

## 2.2 Geotextile filter

Geotextile filters are required to satisfy three requirements: retention, hydraulic conductivity, and clogging. The details of each requirement are given below.

### *2.2.1 Retention criterion*

Inspired by Terzaghi's [1] retention criterion for granular filters (Eq. 1), the retention criteria for geotextile filters are commonly given by Eq. (5). Wilson-Fahmy [10] and Moraci [11] provided an extensive summary of various proposed geotextile design criteria. CFEM [12] provides retention criteria based on the experimental investigation by Lafleur [13]. Giroud [2] developed a rational retention criterion similar to Eq. (5) with a correction factor for soil with $Cu$ (coefficient of uniformity) and density into consideration.

$$O_{95} \leq \alpha d_y \tag{5}$$

where $O_{95}$ is the opening size of filter, $d_y$ is grain size corresponding to $y$ percent passing, and $\alpha$ is the retention ratio.

### *2.2.2 Hydraulic conductivity criterion*

The seepage through geotextile filters is unimpeded if the cross-plane saturated hydraulic conductivity of geotextile ($k_s^{gt}$) is greater than the saturated hydraulic conductivity of soil ($k_s^s$) times an empirical constant ($\gamma$), represented by Eq. (6). Giroud [2] has reported that surplus pressure head is not developed if cross-plane saturated hydraulic conductivity of geotextile ($k_s^{gt}$) is more than the hydraulic gradient in soil ($i_s$) times $k_s^s$ whereas the flow rate in soil-geotextile is more than the soil if $k_s^{gt}$ is more than $k_s^s$, i.e., $\gamma$ is one.

$$k_s^{gt} \geq \gamma k_s^s \tag{6}$$

### *2.2.3 Clogging criterion*

In a bridging structure formation, coarser grains are retained with a partial restriction on the fine grains. Consequently, the migration of fines leads to a partial clogging of geotextile. The extent of clogging depends on the GSD of soil, CSD, and geotextile thickness [18]. The common practice to evaluate clogging potential involves laboratory testing based on in-situ conditions. Numerous test methods have been proposed to evaluate clogging potentials, such as the long-term flow test, hydraulic conductivity ratio test, and the Gradient Ratio (GR) test. Holtz et al. [15] recommended Eq. (7) to be satisfied for less critical or severe conditions and the GR test for critical or extreme conditions.

$$O_{95} \leq 3d_{15} \tag{7}$$

# 3 Improved Design Criteria

The improved design criteria of retention and hydraulic conductivity for granular and geotextile filters are given below.

## 3.1 IMPROVED RETENTION CRITERION

Consider uniform-size (single-sized) grains infiltrating into uniform-size constrictions similar to sieving; the filter is effective if the constriction size is smaller than the grain size, whereas ineffective if the constriction size is larger than the grain size. This analogy is extended to non-uniform size grains by considering a safety margin limit state function for retention requirement as Eq. (8).

$$g\left(P,C\right)=P_i-C_i \tag{8}$$

Here, $P_i$ and $C_i$ represent the samples from GSD and CSD, respectively. If $g \geq 0$, the filter is effective; if $g < 0$, the filter is ineffective. Since $P_i$ and $C_i$ are random variables, there is a probability associated with each value. Therefore, ineffective retention is composed of all possible combinations of constriction sizes smaller than grain size. The sample of GSD and CSD are generated by generating a uniformly distributed random number ($u_i$) in the interval zero and one and projecting the number vertically from the GSD or CSD on the abscissa.

The probability of ineffective retention ($p_r$) is defined as the probability that the constriction size is larger than the grain size. Alternatively, $p_r$ is equal to the fraction of soil grains the filter might fail to retain. The $p_r$ is estimated by performing Monte Carlo simulations using Eq. (9), the estimate converges as the number of samples ($N$) increases.

$$p_r=\frac{\text{number of times}\left(g<0\right)}{N} \tag{9}$$

To limit the excessive washout of soil fines, the infiltrated fines must be trapped to a possible extent within the filter. For a typical soil-filter system, the $p_r$ decreases with each constriction layer along the filtration path as the number of retained grains increases. Therefore, the $p_r$ at the filter thickness must be considered for assessing the soil-filter system.

## 3.2 IMPROVED HYDRAULIC CONDUCTIVITY CRITERION

### *3.2.1 Hydraulic conductivity criterion for granular filters*

For testing soil-filter, a downward flow is simulated in a one-dimensional flow test set up by applying a constant pressure head at the inlet greater than at the exit of the soil-filter system, which is considered the most adverse condition in filtration. The equivalent hydraulic conductivity ($k_s^{sf}$) for the soil-filter system is given by Eq. (10).

$$k_s^{sf}=\frac{t_s+t_f}{\left(t_s/k_s^s\right)+\left(t_f/k_s^f\right)} \tag{10}$$

According to Darcy's law, the flow rate ($Q_s$) through a cylindrical soil column with constant pressure head at boundaries, as shown in Fig. 1, is evaluated using Eq. (11).

$$Q_s=\frac{P_i-P_e+t_s}{t_s}k_s^sA=i_sk_s^sA \tag{11}$$

where, $Q_s$ is the discharge through soil; $i_s$ is the hydraulic gradient in soil; $A$ is the cross-sectional area; $t_s$ and $t_s$ are soil and filter thicknesses, respectively; $P_i$ and $P_e$ are the pressure head at intel and exit, respectively.

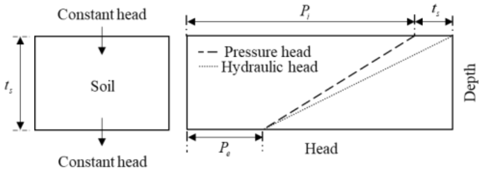

**Fig. 1** Variation of hydraulic head and pressure head along the depth of a soil

Figure 2 shows the variation of hydraulic and pressure heads as a function of depth for the three soil-filter systems. The hydraulic gradient in soil ( $i_s$ ) and hydraulic gradient in filter ( $i_f$ ) in a soil-filter system are defined as Eqs. (12) and (13), respectively.

$$i_s = \frac{\Delta h_s}{t_s} = \frac{P_i - P_{isf} + t_s}{t_s} \tag{12}$$

$$i_f = \frac{P_{isf} - P_e + t_f}{t_f} \tag{13}$$

where, $\Delta h_s$ is the hydraulic head loss in soil and $P_{isf}$ is the pressure head at soil-filter interface.

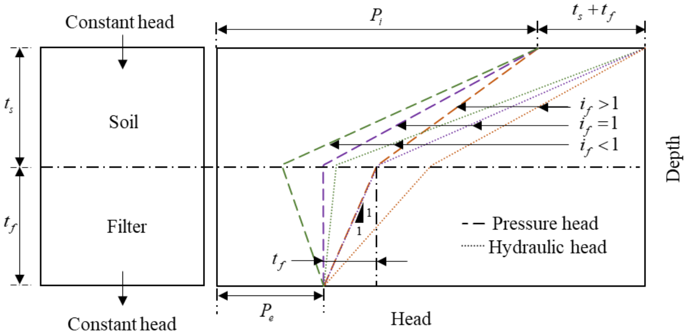

**Fig. 2** Variation of hydraulic head and pressure head along the depth of a soil-filter system

The conservation of mass states that the water flux (flow rate per unit area) in the soil and the filter are the same. Using Darcy's law, water flux through the system ( $v_{sf}$ ) can be expressed as Eq. (14).

$$v_{sf} = k_s^s i_s = k_s^f i_f \tag{14}$$

It can be seen from Fig. 2 that the surplus pressure heads are not developed for a soil-filter with $i_f \le 1$. Equation (14) is rewritten as Eq. (15) by substituting $i_f \le 1$. Equation (15) represents the pressure head requirement of filter, and it is similar to the pressure head criterion proposed by Giroud [2].

$$k_s^f \ge k_s^s i_s \tag{15}$$

The flow rate requirement is established by equating the flow rate in the soil without a filter (Fig. 1) and the flow rate in a soil-filter system (Fig. 2). The filter will be deemed acceptable if the flow rate in the soil-filter system is at least equal to the flow rate in soil. Referring to Fig. 2, the hydraulic gradient in soil-filter system ( $i_{sf}$ ) is defined as Eq. (16).

$$i_{sf} = \frac{\Delta h_{sf}}{t_f + t_s} = \frac{P_i - P_e + t_f + t_s}{t_f + t_s} \tag{16}$$

where $\Delta h_{sf}$ is the hydraulic head loss in soil-filter system.

Substituting Eqs. (10), (12), and (16) in Darcy's law (Eq. 11) give the flow rate in soil and the soil-filter system as Eqs. (17) and (18), respectively.

$$Q_s = k_s i_s A = \frac{P_i - P_e + t_s}{t_s / k_s} A \tag{17}$$

$$Q_{sf} = k_{sf} i_{sf} A = \frac{P_i - P_e + t_s + t_f}{t_s / k_s + t_f / k_f} A \tag{18}$$

Substituting Eqs. (17) and (18) for the requirement of $Q_{sf} \geq Q_s$ and simplification gives Eq. (19).

$$k_s^f \geq k_s^s \frac{P_i - P_e + t_s}{t_s} \tag{19}$$

Equation (19) represents the flow rate requirement and is equivalent to Eq. (15), indicating that both the hydraulic conductivity requirements are satisfied by the sole condition of $k_s^f \geq k_s^s i_s$. The validation of Eq. (15) is provided by Kalore and Sivakumar Babu [16].

The developed criterion is independent of the thickness of filter, indicating the applicability of the criterion to granular and geotextile filters. For granular filters with internally unstable soils, it is observed that the zone of influence is marginal compared to its thickness. Therefore, it is rational to consider the hydraulic conductivity of soil and granular filter without clogging, and the hydraulic conductivity requirements for the granular filter are satisfied by Eq. (15) with internally stable and unstable soils. For nonwoven geotextile filters, the thickness indirectly influences the hydraulic conductivity depending on the mass per unit area. Also, the applicability of the developed criterion is limited to internally stable soils and filters. Geotextile filters are highly susceptible to clogging due to their limited thickness compared to granular filters. The clogging significantly affects the flow through geotextile and is needed to be considered in the design criterion.

### *3.2.2 Hydraulic conductivity criterion for geotextile filters*

The applicability of the developed criterion (Eq. 15) can be extended to internally unstable soils if the hydraulic conductivities of soil and geotextile filters are examined after the formation of the bridging structure. The zone of soil where the significant movement of soil grains is observed to be relatively thin and less than 10 mm for the formation of bridging structure or filter cake formation. Therefore, considering the relative depth of soil (>100mm) compared to the zone of influence, it is rational to consider the hydraulic conductivity of the original soil in the design criterion. For geotextiles, the extent of clogging is a function of retention efficiency and hydraulic properties. Therefore, the hydraulic conductivity criterion considering the partial clogging of geotextile and original soil is given by Eq. (20).

$$k_s^{gc} \geq i_s k_s^s \tag{20}$$

where, $k_s^{gc}$ and $k_s^s$ are the saturated hydraulic conductivities of partially clogged nonwoven geotextile and original soil before re-grading, respectively. The semi-empirical equations to predict the $k_s^{gc}$ and $k_s^s$ are provided elsewhere [17,18,19].

# 4 RESULTS

## 4.1 Estimation of limit state of retention criterion for granular filters

The probability of ineffective retention ($p_r$) is defined as the fraction of soil grains the filter might fail to retain. The $p_r$ is a filter performance indicator regarding the formation of a stable skeleton structure. The data required for the probabilistic assessment involves GSD, relative density, and filter thickness. To consider the soil's fines, which might infiltrate from the soil's coarser matrix to the soil-filter interface, re-grading of soil GSD at 2 mm sieve size for the well-graded soils, whereas re-grading at the point of inflection for the gap-graded soils is considered. The modified Silveira model is implemented to estimate CSD based on the critical review by Wang and Dallo [20].

The $p_r$ is evaluated from the published experimental assessment of the soil-filter system. A total of 56 datasets with 31 effective and 25 ineffective soil-filter systems representing a wide range are used to obtain a limit state of $p_r$. The data details are provided by Kalore et al. [18]. The results are shown in Fig. 3, with each data point representing an individual experimentally assessed soil-filter system. The data points are categorized into effective and ineffective. Figure 3 shows the computed $p_r$ on the y-axis and corresponding ratio of $d_{15}^f/5d_{85}^s$ on the x-axis. The probabilistic assessment criterion performance is compared with the criterion of Terzaghi [1]. Note that $d_{85}$ of soil corresponds to fine fraction GSD re-graded at 4.75 mm. From Fig. 3, three zones are identified as the effective zone ($p_r < 0.5$), marginal zone ($0.5 < p_r < 0.75$), and ineffective zone ($p_r > 0.75$). The result states that the retention is effective, or the stable skeleton structure is developed if the $p_r$ is less than 0.5. The vertical asymptote at $d_{15}^f/5d_{85}^s$ equal to 1 represents Terzaghi's [1] criterion, separating the most effective and ineffective soil-filter systems. The region beyond the left of the vertical asymptote represents the effective zone, while the area beyond the right of the vertical asymptote represents the ineffective zone, as shown in Fig. 3. An assessment criterion performance is governed by the number of ineffective data points in the effective zone. Accordingly, it can be seen from Fig. 3 that all the ineffective soil-filter data points lie above the proposed limit state of $p_r$ equal to 0.5. In contrast, eight ineffective soil-filter data points lie to the left of the vertical asymptote, which violates the Terzaghi [1] criterion.

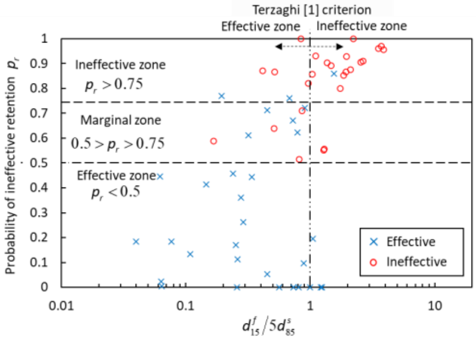

**Fig. 3** Estimation of the limit state of the probability of ineffective retention for granular filters (Note: Details of the experimental data extracted from literature are given by Kalore et al. [18])

### 4.2 Estimation of limit state of retention criterion for geotextile filters

The soil-geotextile compatibility was assessed as effective if the bridging structure is formed, ineffective in hydraulic conductivity requirements if blinding or clogging is observed, and ineffective in retention if excessive erosion is observed. A total of 75 datasets with 54 as effective, 14 as blinding or clogging, and 7 as piping soil-geotextile systems representing a wide range were used from published literature to obtain a limit state of $p_r$.

$p_r$. The details of the data and CSD estimation are provided by Kalore and Sivakumar Babu [19].

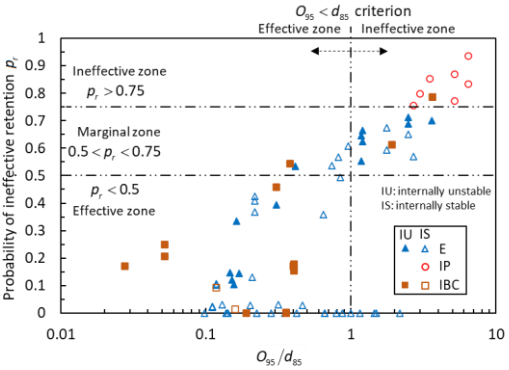

**Fig. 4** Estimation of the limit state of the probability of ineffective retention for geotextile filters (Note: Details of the experimental data extracted from literature are given by Kalore and Sivakumar Babu [19])

The results are shown in Fig. 4, with each data point representing an individual experimentally assessed soil-geotextile system. The points are categorized into Effective (E), Ineffective in Blinding or Clogging (IBC), and Ineffective in Piping (IP). The hollow and solid-filled symbols represent internally stable and unstable soils, respectively. Figure 4 shows the computed $p_r$ on the y-axis and the corresponding ratio of $O_{95}/d_{85}$ on the x-axis. Figure 4 states that the geotextile is effective in retention, or the bridging structure is developed if the $p_r$ is less than 0.75. The $p_r$ equal to 0.75 corresponds to a limit of excessive erosion greater than 2500 g/m$^{2,}$ while the marginal zone is defined for the $p_r$ in the range of 0.5 to 0.75 to represent a moderate erosion greater than 1000 g/m$^2$. Therefore, the region for $p_r > 0.75$ represents an ineffective zone, while $p_r < 0.5$ represents an effective zone. For $p_r$ in the range of 0.5 to 0.75, the effectiveness must be examined following the experimental investigations. The estimated $p_r$ limits for geotextile filters are in good agreement with those estimated for the granular filters, indicating the proposed approach's rationality. It can be seen from Fig. 4 that the proposed criterion could precisely demarcate the effective and ineffective systems in piping compared to the criterion based on representative size ($O_{95} < d_{85}$).

## 4.3 Estimation of limit state of hydraulic conductivity criterion for geotextile filters

The hydraulic conductivity and clogging requirements are satisfied if the condition of $k_s^{gc} \geq i_s k_s^s$ (Eq. 20) is fulfilled. Alternatively, it could be represented as the hydraulic conductivity ratio ($k_s^{gc}/k_s^s$) must be greater than $i_s$. Therefore, the limit state for the failure in satisfying the hydraulic conductivity requirement, i.e., the onset of blinding or clogging, is established by estimating the $k_s^{gc}/k_s^s$ for experimentally assessed soil-geotextile systems discussed earlier.

The results are shown in Fig. 5, computed $k_s^{gc}/k_s^s$ on the y-axis and $O_{95}/d_{15}$ on the x-axis. Blinding or clogging is expected if the ratio $k_s^{gc}/k_s^s$ is less than 1. Note that the criterion is independent of the $i_s$. However, the soil-geotextile systems were assessed experimentally at

https://doi.org/10.1051/e3sconf/202336802015

a hydraulic gradient in the range of 8 to 10. Therefore, it can be interpreted as blinding or clogging is limited if $k_s^{gc}/k_s^s > 1$ for the expected hydraulic gradient of less than 10. The ratio $k_s^{gc}/k_s^s$ clearly separates the Effective (E), Ineffective in Blinding or Clogging (IBC), and Ineffective in Piping (IP) soil-geotextile systems. Holtz et al. [15] criterion is inefficient in demarcating effective and ineffective soil-geotextile systems. Note that the limits developed are applicable for hydraulic gradients less than 10.

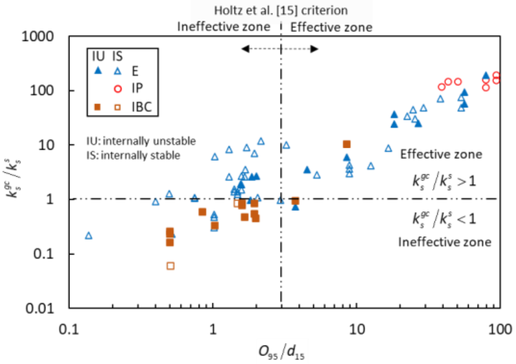

**Fig. 5** Estimation of the limit state of the hydraulic conductivity criterion for geotextile filters (Note: Details of the experimental data extracted from literature are given by Kalore and Sivakumar Babu [19])

## 5 Summary and conclusions

i. This paper presents improved filter design criteria for retention and hydraulic conductivity for granular and geotextile filters. The developed design criteria are based on the complete GSD of soil and the CSD of filter, an important consideration, and improvement over the empirical criteria in published literature. Therefore, the influence of GSD shape is inherently captured in the design. Also, the framework is responsive to filter thickness which was not considered in the existing criteria.

ii. The limit states for the probabilistic assessment for retention requirements are estimated based on the experimental data. The probabilistic assessment considers the most influencing factors, such as GSD, CSD, RD, and filter thickness. The comparison between the probabilistic assessment and other widely-used models has demonstrated the refinement in soil-filter system assessment.

iii. For the hydraulic conductivity requirement of $k_s^f \geq k_s^s i_s$, an analytical criterion is developed considering the governing flow equations for soil-filter system.

iv. The hydraulic conductivity and clogging criteria ensure common requirements of unimpeded flow for effective performance. These requirements are satisfied in the developed approach by considering a criterion based on the hydraulic conductivity of clogged geotextile and soil in contact ($k_s^{gc}/k_s^s > 1$). The hydraulic conductivity of partially clogged geotextile is estimated based on the semi-empirical model. The model has been calibrated to predict the GR test results and depends on the considered test results dataset. The comparison between the proposed and widely used criteria has shown an improvement in the soil-geotextile system assessment.

v. The developed criteria provide a primary means for assessing and designing filters. Experimental or advanced computation-based analysis is suggested for critical structures.

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