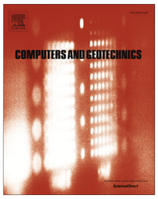
Computers and Geotechnics 84 (2017) 117–128

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo



Research Paper

A network model to assess base-filter combinations

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ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form 16 November 2016
Accepted 21 November 2016
Available online 7 December 2016

Keywords:
Network model
Granular filter
Internal erosion
Voids
Constrictions

ABSTRACT

Granular filters retain base material within the narrowest constrictions of their void network. A direct comparison of the base material particle size distribution (PSD) and the filter constriction size distribution (CSD) cannot easily be used to assess filter-base compatibility. Here a conceptually simple random-walk network model using a filter CSD derived from discrete element modelling and base PSD is used to assess filter-base compatibility. Following verification using experimental data the model is applied to assess empirical ratios between filter and base characteristic diameters. The effects of filter density, void connectivity and blocking in the first few filter layers are highlighted.

1. Introduction

Granular filters play an important role in many geotechnical structures, most notably embankment dams and flood embankments. As outlined in [1] filters downstream of the core can interrupt or halt internal erosion by trapping mobile particles that are entrained in seeping water. The function of a filter (usually comprising a sand or gravel) is to retain a finer base material. Hitherto, filter design has been largely empirical, with consideration of the particle-scale mechanisms based on intuition and highly idealized models. It is generally accepted that both the filter constriction sizes (i.e. the sizes of the pore throats or narrowest points in the void space) and the particle size distribution (PSD) of the finer base material determine whether a base material will be retained in a given filter i.e. the filter and base will be compatible. A representative filter particle size is generally taken to indicate the filter constriction sizes [2]. The development of micro-computed tomography (μCT) and the discrete element method (DEM) mean that the constrictions within a granular material can now be quantified. If both the base PSD and the filter CSD are known and if there is an overlap in the range of sizes covered by each, a simple visual comparison of the distributions will not always indicate whether a filter will prevent unacceptable erosion of base material.

This contribution aims to advance understanding of filter behaviour by using a network-based analysis approach to assess base-filter combinations where the filter CSD is known. The conceptually simple network model uses an area-biased random walk algorithm. CSD data are generated by applying the weighted Delaunay triangulation approach proposed by Reboul et al. [3] to virtual samples created using the discrete element method (DEM). The network model's performance is verified using simple base-filter combinations and experimental data [4]. The "no", "some" and "continuing" base soil erosion categories proposed by Foster and Fell [5] are revisited and the network model is used to explore the filter mechanics in some detail.

2. Background

The classic filter rule proposed by Terzaghi defines an effective filter, i.e. a filter that can retain a given base material, as one with $D_{15F}/D_{85B} \leqslant 4$, where D_{15F} is the filter particle diameter for which 15% of the material by mass is finer and D_{85B} is the base particle diameter for which 85% of the material by mass is finer [6]. In developing this rule, Terzaghi proposed that the characteristic filter particle diameter D_{15F} be considered as a proxy for a characteristic diameter of the constrictions within the filter void network [2] and this concept has been adopted in subsequent studies. In their experimental work, Kenney et al. [4] found that $D_c^* \leqslant D_{15F}/5$ (where D_c^* is the controlling constriction size, taken to be equal to the largest eroded particle) and they advocated the continued use of the Terzaghi relationship. Sherard and Dunnigan [7] also recommend D_{15F} as a characteristic filter diameter for design, but to vary the D_{15F}/D_{85B} ratio depending on the base material being assessed.

For ageing dams with filters which were not designed to meet modern filter requirements, rather than drawing a distinct line

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http://dx.doi.org/10.1016/j.compgeo.2016.11.014

between "effective" and "ineffective" filters, Foster and Fell [5] proposed categorizing filters as follows: (i) "seal with no erosion" where very little material is passed through the filter or is eroded (ii) "seal with some erosion" (iii) "partial or no seal with large erosion" or "continuing erosion" where the filter is too coarse for the base material to seal the filter. As with the Sherard and Dunnigan [7] criteria, the boundary between no erosion and some erosion depends on the base soil under consideration. For base soils with less than 15% cohesive fines, this boundary is drawn at $D_{15F}/D_{85B} \leqslant 7$. For the some/continuing erosion boundary, D_{95B} was found to be a more effective base soil parameter than D_{85B}, and the boundary was drawn at $D_{15F}/D_{95B} \leqslant 9$. The use of relatively large base particles for the characteristic base diameter (i.e. D_{85B} or D_{95B}) shows that the rules implicitly take into account the process of self-filtering, where coarser transported base particles first block the constrictions of the filter and therefore prevent the loss of the finer base particles [8]. This is distinct from clogging of the filter, which Vaughan and Soares [8] defined as "a slow blocking of the filter… generally indicates eventual stability".

DEM enables creation of virtual samples and the particle scale data generated can be analysed to generate a CSD [3,9,10]. It is also now possible to use μCT to directly image filters and algorithms to generate a CSD have been proposed [11–13]. While the availability of filter CSD data enables a more detailed scientific assessment of filter-base interactions, direct comparison with the base PSD reveals little about the filter performance. Analyses that consider the dynamic nature of the filter-base interaction are needed and here a network-based approach is adopted.

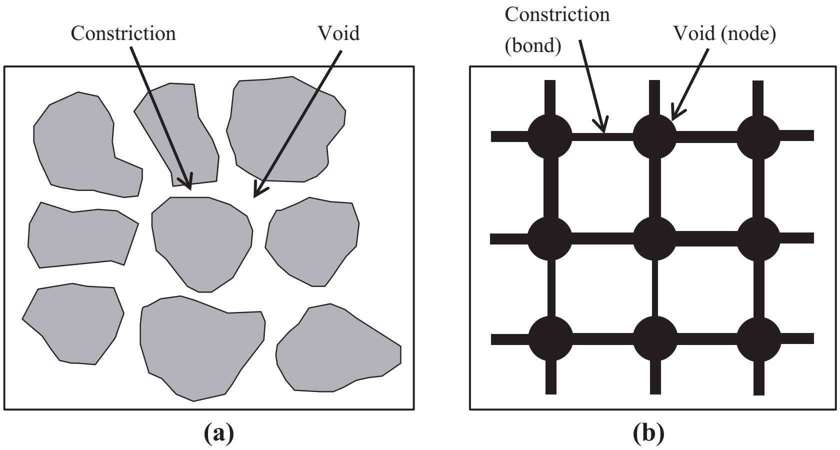
3. Network-based model

Network models to consider pore-scale flow in porous media comprise nodes representing void bodies connected by tubes or bonds that represent the narrowest connecting constrictions or pore throats. This simplified network structure considers only which voids are connected, and the diameter of the narrowest connecting constriction, as shown schematically in Fig. 1. Jang et al. [14] give a general overview of the use of network models in fundamental studies of permeability, multiphase flow and resource recovery. Prior studies that have applied network modelling to study filtration include [15–17]. Many of the network models used to date consider the networks to be arranged as a regular lattice of bonds and nodes, e.g. [14,16]. Following Schuler [18] recent research on granular filters has concentrated on the use of regular cubic networks, i.e. each void has six connections with other voids, one downstream, one upstream and four sideways, e.g. [16,19]. The regular cubic network is justified based on an experimental study reported by Witt [20], who measured pore and constriction distributions in resin-impregnated gravel samples and found an average of 5.7 constrictions per pore body. In Schuler's model the network constrictions are assumed to have randomly assigned diameters to match the CSD. Assuming that each base particle which infiltrates the network is able to infiltrate in either the sideways or downstream directions (i.e. each void has 5 exits, one downstream and 4 sideways). The number of downstream layers through which a base particle of a given diameter can infiltrate can be probabilistically calculated using:

$$n = \frac{\ln(1-\bar{P})}{\ln(P(F))} \tag{1}$$

where $P(F)$ is the probability of a particle moving one layer downstream and $\bar{P}$ is a confidence interval, typically set between 95% and 99%. $P(F)$ is the probability of a particle making a downstream step through the network, which is a function of the probability of a base particle passing through a single constriction. More details on the calculations can be found in [19]. Sjah and Vincens [16] also used this model to back-calculate a CSD curve from experimentally derived number of filter layers through which base particles may infiltrate. A drawback of the probabilistic network model is that it considers the infiltration depth of single particles only. Blocking of constrictions within the filter network and the effect of these blockages on the retention of finer base is not explicitly considered. Semar [21] presented a network model for granular filters to explicitly consider the full CSD. Constrictions were randomly assigned to an initially cubic network to match the CSD. All constrictions smaller than a specified base particle diameter were deleted. If the resulting network percolated (i.e. if there was a continuous path from one side of the filter to the other [22]), the base particle was taken to be susceptible to erosion. As with the probabilistic model, only a single base diameter is considered by a single network simulation. Locke et al. [19] presented a time-dependent model based on a cubic network. Moraci et al. [23] presented a method to predict suffusion using a layer-based model that considers alternate layers of particles and constrictions [23] where the CSD is obtained using the Silveira method [24].

Here a new network model is proposed which is able to account for a polydisperse base PSD and can therefore model the processes of clogging and self-filtering. The model simulates the inter-void movement of particles matching the base PSD using a timestepping, area-biased random walk algorithm. The regular cubic network topology adopted by previous researchers in the field of granular filters is adopted here, as shown schematically in Fig. 2.



(a) (b)

Fig. 1. (a) Schematic diagram of void fabric; (b) representation of void fabric in a network model.