A numerical approach for the determination of the primary fabric of granular soils

TO Huu Duc[1, a], GALINDO-TORRES Sergio Andres[1,b] and SCHEUERMANN Alexander[1,c]

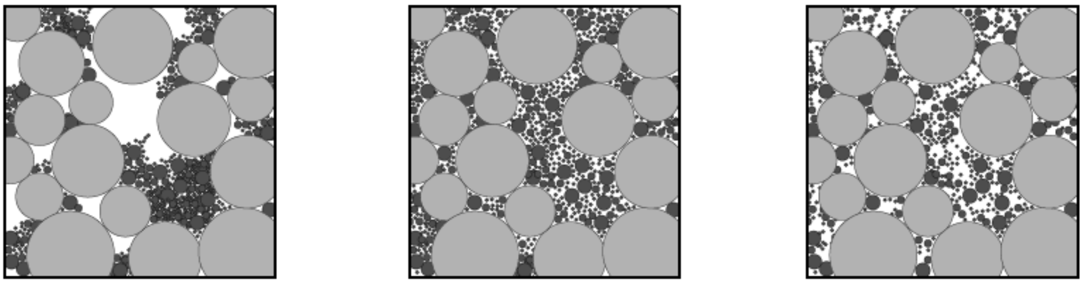
[1]School of Civil Engineering, The University of Queensland
St Lucia, QLD 4072, Brisbane, Queensland, Australia
[a]h.to@uq.edu.au, [b]s.galindotorres@uq.edu.au, [c]a.scheuermann@uq.edu.au

Keywords: Discrete element method, particle arrangement method, soil, simulation, primary fabric, oedometric test

Abstract. *Granular soil as a porous medium consists of particles, touching each other and forming a solid skeleton with interconnected pores. The transfer of externally applied loads is in most cases not homogeneous, but takes place mostly in a limited number of particles creating so-called force chains. The assembly of force chains is frequently referred to the primary fabric of a soil. The knowledge of the primary fabric is of vital importance for the analysis of many soil behaviours as, for instance, in the assessment of suffusion. Most of the current numerical models, mostly based on a discrete element approach, generate an artificial soil specimen by creating particles randomly. Therefore, particle position is not under control at all, and as a consequence the influence from particle arrangement on the creation of the primary fabric is neglected. This paper presents a sequential packing method, which allows studying two different types of particle arrangements for a given and constant grain size distribution: (1) layer-wise, producing a layered structure and (2) discrete, leading to a rather homogeneous soil structure. The generated soil specimens are compacted using a discrete element model under oedometric boundary conditions and zero gravity to create force chains within the soil structure. These force chains are then analysed to determine the soil fraction contributing to the load transfer. The results of the study provide an evidence of the influence of the particle arrangements on the appearance of the soil skeleton and the fraction of particles involved.*

Introduction

Soil is not only the most popular material for hydraulic structures, such as embankment dams; it is also the foundation for most civil engineering structures. Organic free soil, as a typical porous medium, consists of solid particles and pores filled with water and air. In granular soils generally only the particles take over and transfer the externally applied load. However, the contribution of each particle in the load transfer varies. Particularly in well graded soils, coarse particles are often in contact with many other particles creating *force chains*, which means a chain of particles transferring the load from one end of the specimen to the other. Particles included in these force chains are kept firmly in their position and form the soil *primary fabric* (PF) [4] which is also referred to as the *soil skeleton*. Otherwise, the fraction of fine particles fills the pores created by the PF. These particles can be referred to as *loose particles* (LP), which are kept in the pores of the PF and support only the weight of other fine particles above (Fig. 1).



a) Initial stability b) Mobilisation c) Particle loss

Fig. 1 PF (coarse grey particles) and LP (fine black particles) in suffusion process [9]

The determination of the PF, as well as the determination of LP, is of vital importance for many soil behaviour analyses such as load distribution and internal stability. Commonly, it is not known which fraction of the soil contributes to the PF. However, it allows applying filtration studies and filter criteria for example for the assessment of suffusion, when the PF, playing the role of filter, and LP, playing the role of base, are separated clearly [3, 8]. Nonetheless, there are not many methods available for the differentiation of PF and LP. An empirically derived method determines the minimum PF mass by an average void ratio of the PF, e_p, and porosity of LP, n_l [4]. Another recent study suggested a calculation of the maximum LP mass by LP porosity, density and PF volume [3]. In both methods, the determination of the input parameters is not clear, which hinders a practical use.

This paper provides a numerical approach for determining the PF of a given grain size distribution by number of particles and mass fraction. Moreover, calculation results highlight the impracticability of an assumption of a sharp transition between filter and base referred to as delimiting point [3], or inflection point [6]. The paper also contributes a novel study on the influence of particles arrangement on the resulting PF, which is often overlooked in empirical studies [11].

2. Simulation algorithm

While many similar researches are based on commercial software tools such as PFC3D [5, 7], the numerical simulation presented here was developed as an authorial open source code, which is built in C++ using the Mechsys library [1], developed partly by the authors as well. This code can be optimized during the compilation to make the simulation much faster than usual.

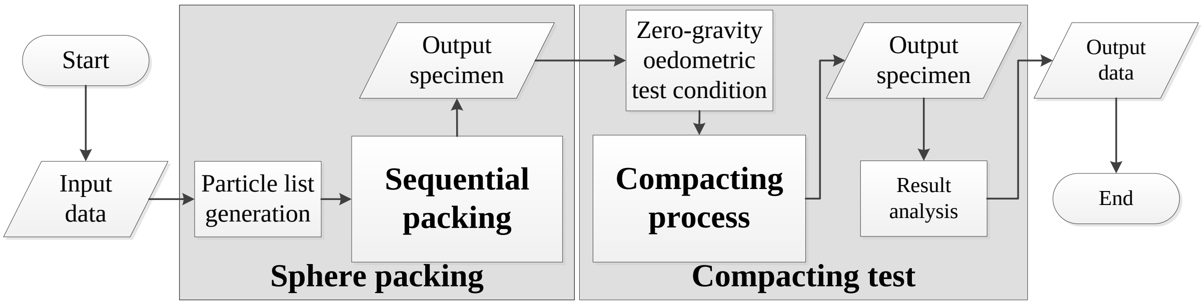


Fig. 2 Numerical approach for determining PF

In the current code only spherical particles are considered due to reasons of simplicity and applicability for the calculation methods with the aim of modelling a significant amount of particles. However, the use of particles with general shapes has been approached by the authors [2, 10] and is in principle possible for future studies. The assumption of having only spherical particles is acceptable for non-cohesive, granular soils and is frequently used by other similar researches [5, 7]. The numerical approach consists of two main parts: sphere packing and compaction test (Fig. 2).

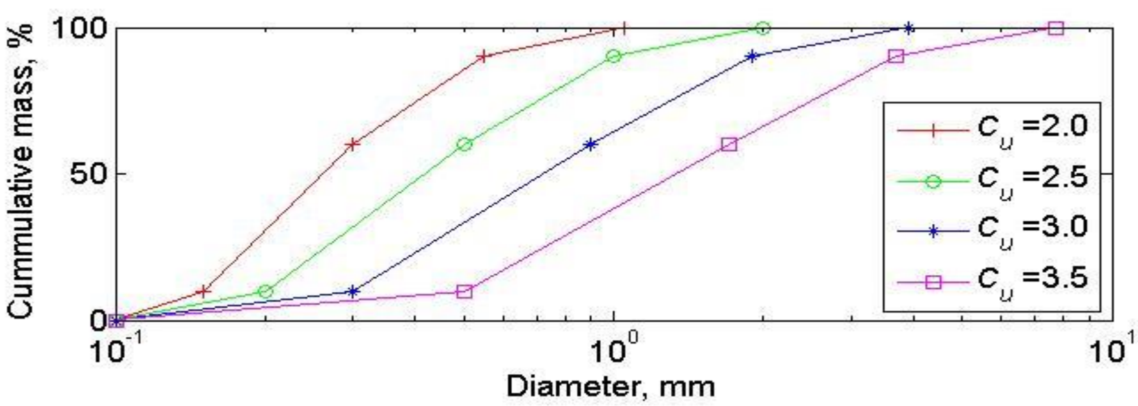
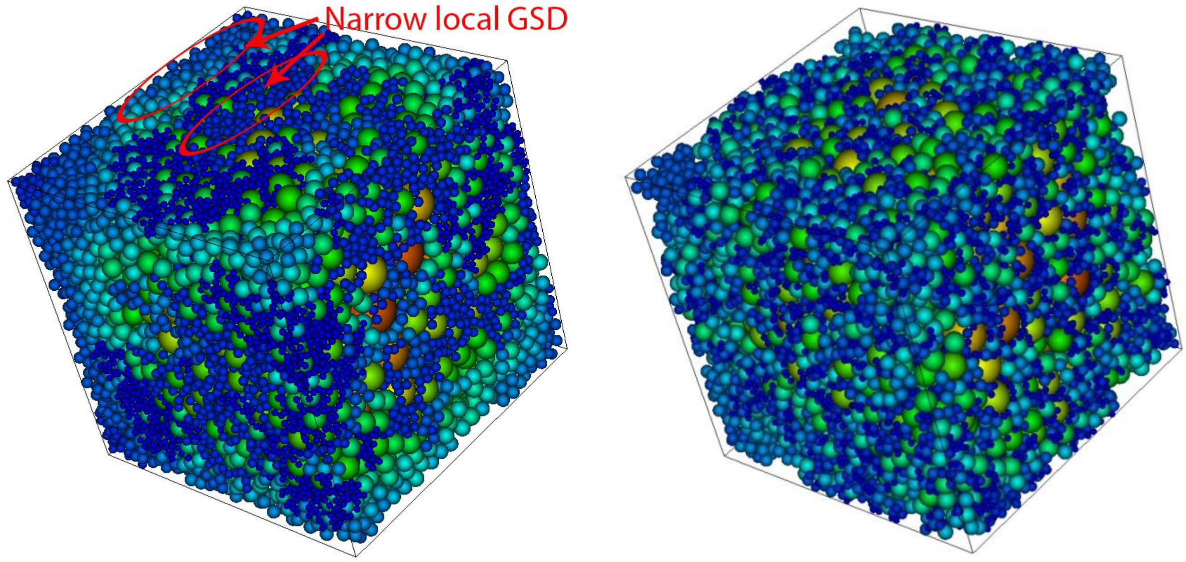


Fig. 3 Grain size distribution of soils used for the study

Regarding the first part, a list of particles are generated before the sequential packing process according to the grain size distribution (GSD), the predefined volume of specimen and its porosity.

All generated specimens have the same porosity, $n = 0.35$, and the coefficient of uniform, C_u, is varied from 2.0 to 3.5 (Fig 3). The soils with $C_u < 3$ are considered as *narrow-graded* (NG) soils, and the rest is classified as *wide-graded* (WG) soils according to [4]. The GSD is divided into 20 intervals of 5% by mass. Each interval defines a mean diameter set to all particles in the given interval. Although this division reduces the ratio d_{max}/d_{min} at some level, it does not influence much the GSD. The number of particles must be an integer number. Abundant mass of a coarse interval is therefore transferred to the next finer interval.



a) Layer-wise arrangement b) Discrete arrangement

Fig. 4 Particle arrangements studied in the simulation

In most of the prior, similar numerical models, particles are generated randomly [5-7] hence, the particles arrangement was not controlled and, therefore, neglected. The presented approach employed a sequential packing algorithm, which has a better particle position control. Four particles are added first to build a tetrahedron with 4 faces, each of which consists of three particles. Afterthat, another particle is adjusted to one face to build a new tetrahedron with three new faces. The process is repeated until the moment when all particles are packed. If the particles are added by descending order of size, the soil specimen will tend to create a *layer-wise arrangement* (LA), where the neighbouring particles have similar sizes (Fig. 4a). Otherwise, when the fine particles have priority to be put between the coarse particles, the specimen shows a *discrete arrangement* (DA), which is more homogenous in comparison with the LA (Fig. 4b). Moreover, this semi-analytical method for sphere packings takes only just over 20 minutes of calculation with a singular computational core 2.7 GHz for 77000 particles. More details of the sequential packing algorithm can be found in [11].

In the secon part of the simulation, the visual oedometric test and zero gravity conditions are applied by the DEM model (Fig. 5). The parameters of the DEM simulation are represented in Table 1. Since it is difficult for the determination of the PF to separate forces created by self-weight of particles and created by external load, all particles are set to be free from gravity. As a result, only particles belonging to the PF are kept firmly within particle chains, crossing each other, and have at least four contacts with other particles and/or boundary walls.

The line called *force chain* connects the centres of particles in a chain and represents the *normal contact force* (NCF) acting between them. Their magnitude are visualised in Fig. 6 by its thickness and colour. Because the paper focus only on the primary fabriction determination, the tangential contact forces are not illustrated. Meanwhile, the LP tend to have no contact forces because the NCF of the PF pushes them out of their position. The force chain data are then analysed by a Matlab code to identify PF and LP of the soil specimen.

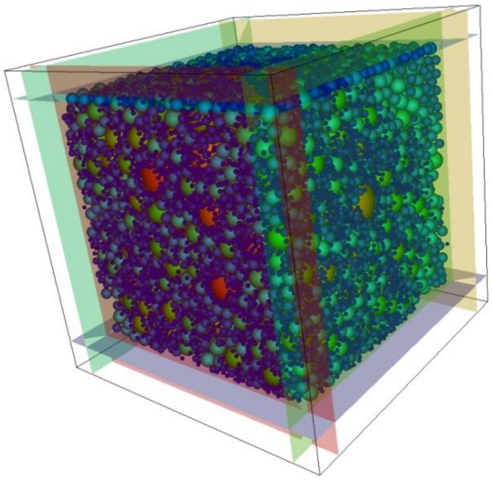
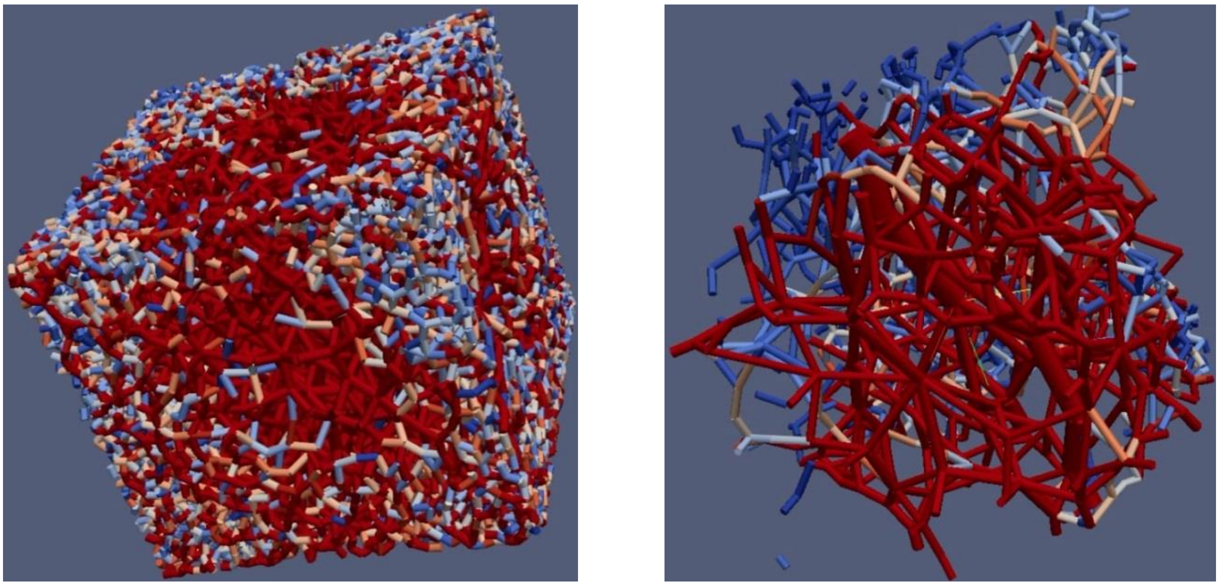


Fig. 5 Oedometric boundary conditions for the DEM test

Table 1. DEM simulation parameters

Parameters	Value
Gravity constant, g [m/s^2]	0
Normal stiffness, K_n [N/m]	$2.0{\cdot}10^7$
Tangential stiffness, K_t [N/m]	$2.0{\cdot}10^7$
Normal viscous coefficient, G_n [s^{-1}]	$1.6{\cdot}10^4$
Tangential viscous coefficient, G_t [s^{-1}]	$0.8{\cdot}10^4$
Time step, dt [s]	$3.2{\cdot}10^{-10}$
Intermediate output time, d_{tout} [s]	$3.2{\cdot}10^{-4}$
Total time of simulation, t_f [s]	$1.2{\cdot}10^{-2}$
Limit Kinematic energy, K [Nm]	10^{-7}
Rolling stiffness coefficient, β	0.12
Plastic moment coefficient, η	1.0



a) Narrow-graded, layer-wise arrangement   b) wide-graded, discrete arrangement

Fig. 6 Force chains under oedometric load and zero gravity

3. Results and discussion

There is an obvious trend that narrow-graded, LA soils involve more particles in their PF, which lead to a bigger proportion by number, as well as by mass, of PF (Fig. 7, Fig. 8). The immediate reason of this trend is that a particle in LA often has the similar size to its neighbours, which makes the local GSD narrower than the global GSD. Meanwhile, because the fine and coarse particles are put nearby in LA, the local GSD turns to a gap-graded one.

The phenomenon is severe for the narrow-graded soils, where the PF involves a double amount of particles with LA in comparison with DA (Fig. 7). In this case, the load applied to the soils with LA are better distributed in a denser particle network. However, when the GSD spreads widely enough, but is still divided into only 20 intervals, the difference between the mean sizes of close intervals becomes significant, which makes the influence of the particle arrangement less severe. This influence of the gap-graded gradation is demonstrated vividly by the test results of the soils with C_u=3.5 (Fig. 7, Fig. 8).

The LA has a practical meaning, that it simulates real soil dumped from trucks on construction sites: coarse particles drop faster and farther, while fine particles take more time for the slide and the suspension before they settle. However, the results are not implying that the segregated soil is practically more secure than the homogeneous soil. When the new mass of soil is dumped on the previous mass, the coarse particles may come in contact directly with the prior fine particles. As a consequence, the local narrow-graded GSD might turn to a gap-graded one.

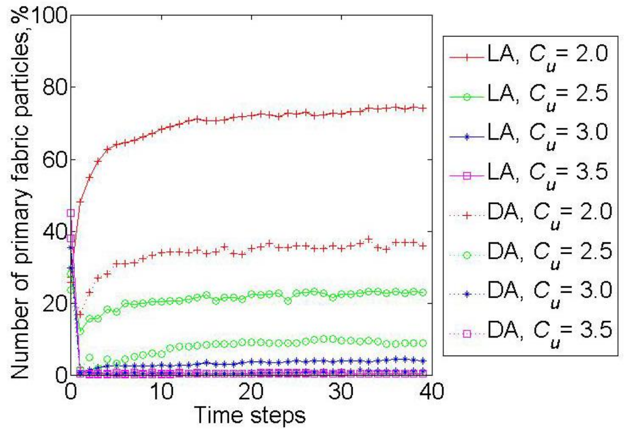


Fig. 7 Proportion by number of primary fabric particles

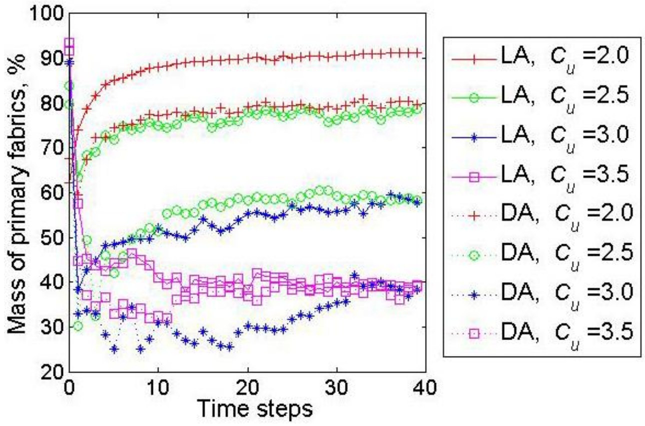


Fig. 8 Proportion by mass of primary fabrics

The quantitative results show that the PF of the wide-graded soils may take only just over 2% by number of particles (Fig. 7), but it contributes just under 40% by mass (Fig. 8). This fact is contrary to previous empirical estimates that LP in wide-graded soils takes less than 20% of the total soil mass [4]. The study conducted by [4] is based on the common assumption that the GSD of soil can be cut into two parts by a delimiting value. All particles smaller than that value are considered being attributed to LP and vice versa. This assumption of having a sharp delimiting value was also used by sequential empirical studies [3, 8] mainly due to the significant challenge to determine empirically the load distribution on each soil particle.

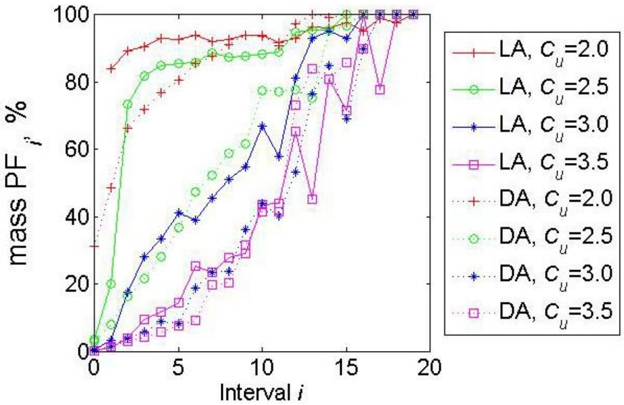


Fig. 9 Contribution to primary fabric in each intervals

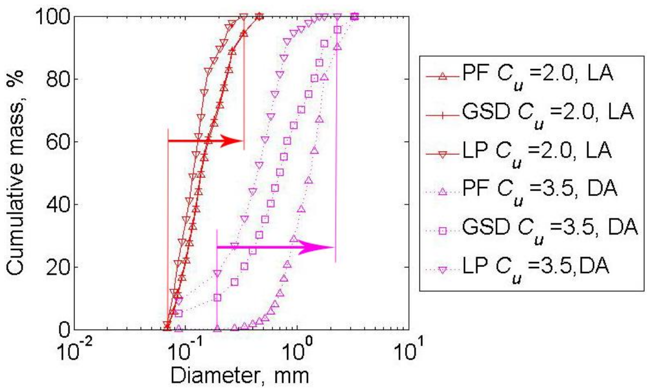


Fig. 10 Overlapping zone between primary fabric and loose particles

Nevertheless, the numerical force chain analysis is able to identify the stress state of all particles, which shows that most of the intervals of a given GSD contribute, to some extent, to both LP and PF (Fig. 9). The *overlapping zone* between PF and LP in GSD in both narrow and wide-graded soils cannot be overlooked because of its wide range (Fig. 10) of more than 60% of the soil mass (Fig. 9). A note should be left here that there are always some fine particle kept accidentally in the force chains, therefore, the OZ is considered to start from more than 1% of the PF mass (Fig. 10).

4. Conclusion

By way of conclusion, the simulation is able to determine soil PF and LP, which is important for many soil behaviour analyses. In addition, the results of the study highlight that there is no sharp boundary between PF and LP in the soil GSD. The approaches based on the assumption of that sharp boundary [3, 4, 8] might be applicable, but they consequently neglect the important phenomenon of having an overlapping zone between PF and LP.

In addition, the simulation also provides a key understanding about the influence of the particle arrangement on the development of the PF and its behaviour under load. This is one important characteristic of a soil, which was often overlooked and neglected in prior empirical studies [12].

The future work aims to involve seepage flow into the simulation to have a precise view on the detachment of soil particles from the PF.

5. Acknowledgement

The research is covered by Discovery Project (DP120102188) – "Hydraulic erosion of granular materials" from the Australian Research Council (ARC). The first author is funded by a scholarship from 322 projects of Ministry of Education and Training of Vietnam (MOET), a top-up scholarship and GSITA from The University of Queensland (UQ).

6. References

1. *Mechsys homepage*. Available from: http://mechsys.nongnu.org/index.shtml.
2. Galindo-Torres, S., et al., *Breaking processes in three-dimensional bonded granular materials with general shapes.* Computer Physics Communications, 2012. **183**(2): p. 266-277.
3. Indraratna, B., V.T. Nguyen, and C. Rujikiatkamjorn, *Assessing the potential of internal erosion and suffusion of granular soils.* Journal of Geotechnical and Geoenvironmental Engineering, 2011. **137**(5): p. 550-554.
4. Kenney, T. and D. Lau, *Internal stability of granular filters.* Canadian Geotechnical Journal, 1985. **22**(2): p. 215-225.
5. Reboul, N., E. Vincens, and B. Cambou, *A computational procedure to assess the distribution of constriction sizes for an assembly of spheres.* Computers and Geotechnics, 2010. **37**(1): p. 195-206.
6. Semar, O., K.J. Witt, and R.J. Fannin. *Suffusion Evaluation-Comparison of Current Approaches*. in *Proceedings of the Fifth International Conference on Scour and Erosion, Geotechnical special Publication*. 2010.
7. Shire, T. and C. O'Sullivan, *Micromechanical assessment of an internal stability criterion.* Acta Geotechnica, 2013. **8**(1): p. 81-90.
8. Skempton, A. and J. Brogan, *Experiments on piping in sandy gravels.* Geotechnique, 1994. **44**(3): p. 449-460.
9. Steeb, H., *Non-Equilibrium Processes in Porous Media.* Habilitation, Universität des Saarlands, Saarbrücken, 2008.
10. To, H.D., A. Scheuermann, and S. Galindo-Torres, *Numerical modelling of soil porous structure,* in *Infiltratiton instabilities in granular materials: theory and experiments*. 2012: Brisbane.
11. To, H.D., A. Scheuermann, and D.J. Williams. *A new simple model for the determination of the pore constriction size distribution*. in *6th International Conference on Scour and Erosion (ICSE-6)*. 2012. Société Hydrotechnique de France (SHF).
12. Wan, C.F. and R. Fell, *Assessing the potential of internal instability and suffusion in embankment dams and their foundations.* Journal of Geotechnical and Geoenvironmental Engineering, 2008. **134**(3): p. 401-407.