A particle-scale perspective on internal erosion: Observations from computational simulations and physical experiments

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ABSTRACT

This study presents particle-scale insights into internal erosion mechanisms using computational simulations and physical experiments. Existing design criteria to determine the susceptibility of soils to initiation mechanisms, along with filter criterion for assessing continuation have been predominantly developed based on macro-scale observations. However, limited studies have explored the underlying particle-scale mechanisms. As internal erosion involves the detachment and transport of particles due to seepage, the mechanisms that lead to the initiation and continuation of erosion are rooted at the particle-scale. Computational simulations were performed using the discrete element method which investigated the stress distribution in gap-graded soils. A key finding is that under anisotropic loading conditions, certain transitional gap-graded soils can change from being fines-dominated to coarse-dominated, and hence, their susceptibility to suffusion may change under the anisotropic loading conditions. Physical experiments were conducted using a purpose-built coaxial permeameter cell that utilised spatial time domain reflectometry, an electromagnetic observational method which enabled near-continuous measurement of local porosity during the erosion process. This enabled physical insights into the changes in the internal structure of the soil during filtration experiments. By varying particle sizes and hydraulic boundary conditions, the influence of geometric and hydraulic criteria was investigated. These particle-scale findings can improve the robustness and reliability of existing tools, whilst leading to the development of new techniques to investigate and assess internal erosion.

Keywords: internal erosion, filtration, suffusion, discrete element method, spatial TDR

1 INTRODUCTION

Internal erosion is an important element in the geotechnical design of dams, levees, and other water-retaining structures. Internal erosion occurs when soil particles within an embankment or the foundations of a structure are detached and transported by seepage flows. Internal erosion has been attributed to approximately half of all embankment dam failures globally (Foster et al., 2000). The process of internal erosion is not easily observable or measurable as it occurs within the structure and its foundations, and hence, is a poorly understood phenomenon. There is a need to move away from empirical and rule-of-thumb guidelines into a design philosophy based on underlying mechanics and a rigorous scientific process. This can be achieved by considering particle-scale observations to complement existing macro-scale knowledge, thereby providing a holistic view of the internal erosion mechanisms.

The internal erosion process can be delineated into four main phases: initiation, continuation, progression, and breach (Fell et al., 2015). Existing design approaches focus on minimising the potential for initiation mechanisms to occur and/or preventing continuation, as failure may develop quickly from initiation to breach in hours or days (Fell et al., 2009). The main design consideration to mitigate internal erosion failure is the provision of filters. Modern filter design aims to specify the range of particle sizes to prevent the erosion of soil particles, whilst maintaining sufficient drainage capacity. The performance of a filter in its retention function is clearly rooted at the particle-scale with the trapping of discrete particles. Therefore, the choice of these particle-scale characteristics of a filter is an important design consideration for protecting water retaining structures against internal erosion failure.

A recent technical bulletin summarises the current state-of-knowledge with respect to internal erosion and outlines the initiation mechanisms, including concentrated leak, backwards erosion piping, contact erosion, and suffusion (ICOLD, 2017). Concentrated leak occurs when an opening or crack is formed with subsequent expansion due to erosion of particles from the sides of the opening. Backwards erosion piping initiates at the downstream side, where the eroded particles gradually lead to the formation of a pipe structure that extends towards the upstream side of the dam or levee. Contact erosion occurs at the interface of a finer soil layer and coarser soil layer, where seepage results in the detachment and transport of finer soil particles into the pore space formed by the coarser particles. The term contact erosion is used when seepage flow is parallel to the interface between a finer and coarser layer, while it is typically referred to as filtration when flow is perpendicular to the interface (Beguin et al. 2012). Suffusion occurs in soils with a mixture of finer and coarser soil fractions (e.g., gap-graded soils or widely graded soils) and results in preferential erosion of the finer fraction of the soil. When the fines content is relatively small, suffusion may not lead to changes in the structure or fabric of the coarser fraction, which generally only occurs at higher fines content when the finer particles are contributing to the stress transmission process. An important message to highlight is that all initiation mechanisms involve particle-scale behaviour with the detachment and transport of discrete particles. Hence, it is essential to explore particle-scale mechanisms as the internal erosion process is rooted at the particle-scale.

While the importance of particle-scale observations has been highlighted above, prior studies in the field of internal erosion have focused on macro-scale observations from physical laboratory experiments. Geometric, hydraulic, and mechanical criteria for the initiation and continuation of internal erosion have been extensively developed from macro-scale laboratory investigations. Geometric criteria have been widely used in the design of filters (Terzaghi & Peck, 1948; Sherard et al., 1984) and to assess the internal instability of soil (Kezdi, 1979; Kenney & Lau, 1985). A hydraulic criterion based on the critical seepage velocity for contact erosion was proposed by Brauns (1985), while Ziems (1969) proposed a critical hydraulic gradient for filtration. Skempton and Brogan (1994) suggested a stress reduction factor to account for the reduced effective stress carried by the finer fraction of a soil, which provided a means to understanding why suffusion initiated at hydraulic gradients less than the critical hydraulic gradient for heave failure. In addition to design criteria, observations of particle transport and changes in porosity have focused on macro-scale observations. Existing approaches to measure changes in porosity due to internal erosion have considered the cumulative loss of fine particles (Ke and Takahashi 2014; Rochim et al. 2017), or visual observation of changes in layer heights and post-test sampling (Ke and Takahashi 2012), without probing the changes in the internal structure of an eroded soil mass.

These shortcomings are a result of the available resources to probe the particle-scale characteristics of internal erosion and highlights the need to develop fundamental particle-scale understanding of internal erosion mechanisms. New experimental methods such as the application of electromagnetic observational techniques have enabled the internal structure to be observed and corresponding particle-scale mechanisms to be measured. Coupled with this is ever-increasing computing power, which has enabled large-scale simulations to uncover the influence of particle-scale interactions. This study combines computational and physical experiments to link particle-scale processes with macro-scale observations. The Discrete Element Method (DEM) was employed to enable an improved understanding of how stresses are redistributed in internally unstable soils for anisotropic stress conditions, with findings challenging the current assessment of susceptibility to suffusion. In addition, the migration of erodible particles was explored using spatial time domain reflectometry and a purpose-built coaxial permeameter cell, providing near-instantaneous and near-continuous porosity profile during the initiation and continuation phase of filtration. The combined computational and physical particle-scale observations provided a holistic view of the internal erosion process.

2 OBSERVATIONS FROM COMPUTATIONAL SIMULATIONS

In most physical experiments, it is prohibitive to obtain data regarding particle interactions, including the inter-particle contact forces, which is an important feature in understanding how stresses are transmitted through an internally unstable granular soil. The Discrete Element Method (DEM) provides a computational route to simulate the movement of individual particles according to Newtonian laws of motion (Cundall & Strack, 1979). This study presents the results of a wide range of DEM simulations on granular gap-graded soils that are susceptible to suffusion to investigate how the stress is distributed between the finer and coarser fraction of the gap-graded soil under anisotropic loading conditions.

DEM simulations of constant mean stress triaxial compression tests on idealised spherical assemblies of gap-graded soils were conducted using the open-source software LAMMPS (Plimpton, 1995). Relatively dense samples were generated with a wide range of fines content and size ratios. The particle size distributions (PSD) of the samples are shown in Figure 1. The fines content specified in Figure 1 covers gap-graded soils with an underfilled fabric through to those with an overfilled fabric. A soil with an underfilled fabric is generally observed for fines content less than 24%, and the stress is predominantly transmitted through the coarser fraction. For soils with an overfilled fabric (fines content greater than 35%), the stress is distributed among both the finer and coarser fraction. For soils with a fines content between 24% and 35%, the fabric is regarded as being transitional. In addition, the size ratio, defined as the ratio of the maximum to minimum particle sizes, varied from being internally unstable, borderline unstable, and internally stable according to the Kezdi (1979) criteria. This systematic approach allowed for the complete spectrum of behaviour associated with suffusive soils to be investigated. The samples comprised between approximately 68,500 particles and 3.29 million particles, depending on fines content and size ratio, making these simulations the largest conducted within the geotechnical literature (Sufian et al., 2021). A constant mean stress triaxial compression test was chosen to investigate the role of increasing deviatoric stress, as most existing studies focussed on isotropic stress conditions.

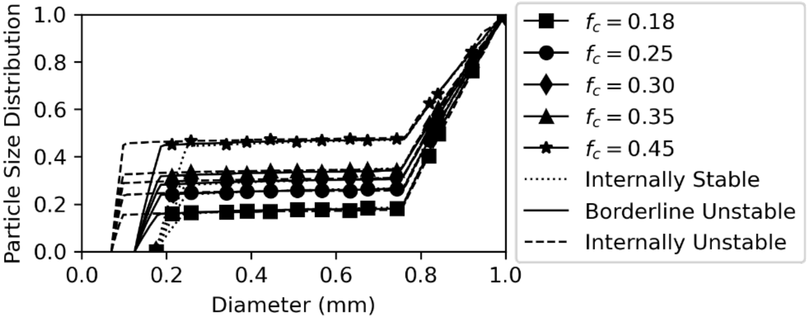
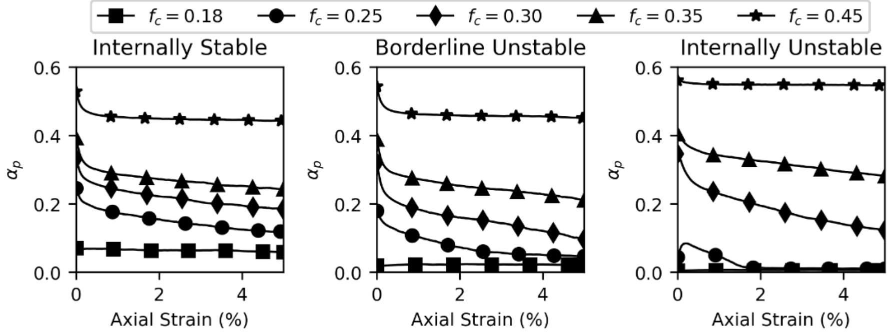
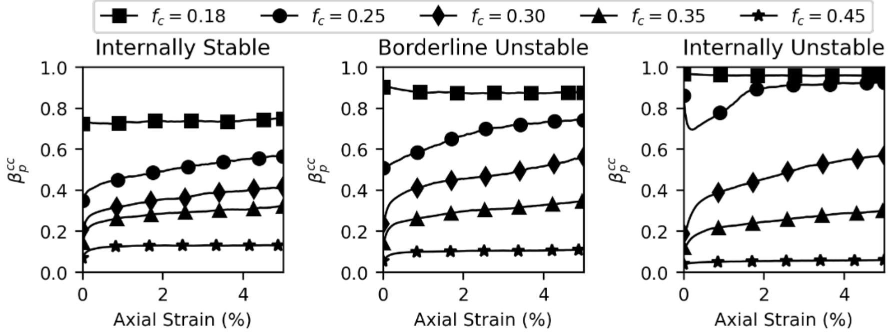


Figure 1: Particle size distribution of the samples used in DEM simulations.

A wide range of particle-based and contact-based data was generated from DEM simulations. In this study, the quantities of interest are the contact forces between particles, and the mean stress on an individual particle. For a gap-graded soil, particle-based quantities can be partitioned between the finer and coarser fraction. The mean stress carried by the finer fraction was defined by α_p. This is similar to the stress reduction factor proposed by Skempton and Brogan (1994), except that α_p is bound between $0 \leq \alpha_p \leq 1$. When considering inter-particle contacts, the mean stress can be partitioned by that transmitted at contacts between the fine-fine particles (β_p^{ff}), fine-coarse particles (β_p^{fc}), and coarse-coarse particles (β_p^{cc}), where all three β_p quantities are bound between $0 \leq \beta_p \leq 1$.



(a) Evolution of α_p



(b) Evolution of β_p^{cc}

Figure 2: Particle-scale stress distribution during constant mean stress triaxial compression tests.

The evolution of α_p throughout the constant mean stress triaxial compression test is shown in Figure 2a. Irrespective of the degree of internal instability, the mean stress carried by the finer fraction increased with increasing fines content. For underfilled soils, α_p reduced with increasing size ratio, while for overfilled fabrics, α_p increased with increasing size ratio. For transitional soils, the trend is less clear, but there is an important observation associated with the evolution of α_p for transitional soils. While α_p changes minimally for underfilled and overfilled soils, a significant reduction in the stress carried by the finer fraction is noted for transitional soils. In some instances, an approximately 50% reduction in the mean stress can be observed. This is important because a soil is more prone to suffusion when the stress carried by the finer fraction is relatively low. The observations in Figure 2a indicate that the soils that were previously not considered susceptible to suffusion may become susceptible to suffusion when subject to anisotropic stress conditions. While internal instability is generally considered through the application of geometric criteria, these influences of the mechanical condition should be considered.

To better understand the transition from coarse dominated to fines dominated behaviour of gap-graded soils, it was necessary to investigate the evolution of β_p^{ff}, β_p^{fc}, and β_p^{cc} during the constant mean stress triaxial compression tests. The evolution of β_p^{cc} is shown in Figure 2b and exhibited an inverse trend to that observed in Figure 2a. Of particular interest was the identification of which of the three β_p were the dominant case in each simulation, from which the following characteristics were obtained:

- $\beta_p^{cc} \geq \beta_p^{fc} \geq \beta_p^{ff}$: coarse-dominated behaviour (C)
- $\beta_p^{fc} \geq \beta_p^{cc} \geq \beta_p^{ff}$: transitional coarse-dominated behaviour (TC)
- $\beta_p^{fc} \geq \beta_p^{ff} \geq \beta_p^{cc}$: transitional fines-dominated behaviour (TF)
- $\beta_p^{ff} \geq \beta_p^{fc} \geq \beta_p^{cc}$: fines-dominated behaviour (F)

While some samples remained in one of the above-listed behaviours throughout the simulation, those with a transitional fabric exhibited a tendency to become coarse dominated for anisotropic loading conditions. While only limited set of data points is available from these simulations, Figure 3 presents a preliminary chart to identify the influence of fines fraction and size ratio on the susceptibility to change behaviour under anisotropic loading conditions. Further research is required to assess and quantify the potential for transitional soils to become coarse dominated more accurately.

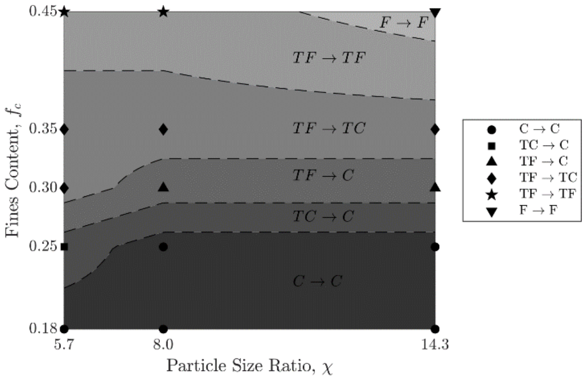


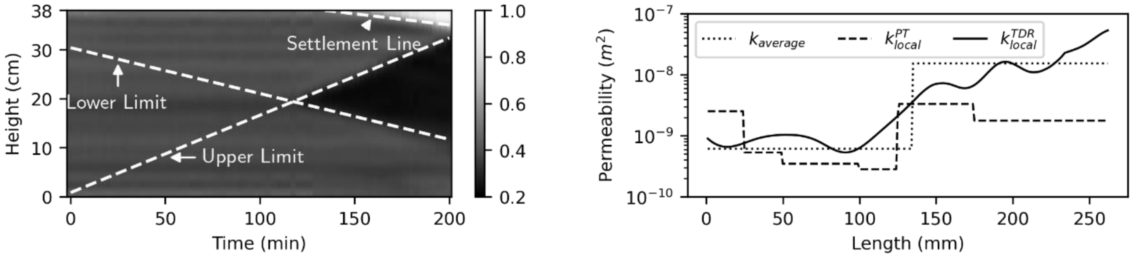
Figure 3: Redistribution of stress in gap-graded soils during anisotropic loading

3 OBSERVATIONS FROM PHYSICAL EXPERIMENTS

Internal particle-scale observations are prohibitive in most physical experiments which either measure macro-scale quantities across the complete sample or make observations of local characteristics by only considering external measurements. Given that internal erosion involves the internal change in structure of a soil, there is a need to physically observe particle-scale characteristics during the erosion process. A potential approach to investigate this is the application of spatial time domain reflectometry (spatial TDR), an electromagnetic observational method capable of measuring the water content and density (Scheuermann, 2012). The application of spatial TDR for internal erosion problems is limited and this study demonstrates how particle-scale internal observations can be inferred from spatial TDR data obtained from filtration and suffusion tests. The experiments were conducted in a purpose-built coaxial permeameter cell (Bittner et al., 2019, Sufian et al., 2022). The permeameter was copper-built with an inner and outer conductor that effectively acted as a coaxial transmission line to enable electromagnetic measurements along the length of the sample. The measured electrical signal was then processed via a forward inversion algorithm to obtain the local porosity along the sample. A central feature in filtration and suffusion experiments is the detachment and transport of finer soil particles through the pore space of the coarser particles. This results in a local change in porosity within the sample as the finer particles fill the pore space between coarser particles, and this local change in porosity is measured using the coaxial permeameter cell.

A set of filtration tests were conducted with a finer soil layer (base layer) underlying a coarser soil layer (filter layer) with upward flow resulting in the migration of the particles from the base to the filter layer. The experiments considered different particle sizes for the base and filter layer, along with different hydraulic boundary conditions to investigate both the geometric and hydraulic conditions on filtration. The choice of base and filter layers were such that they were incompatible and exceeded the continuing erosion boundary proposed by Foster and Fell (2001). This was deliberately selected so that the entire filtration process could be investigated from initiation to continuation to complete washout of the finer base particles, all whilst the internal structure of the soil could be measured via spatial TDR.

The principal data obtained from spatial TDR analysis of the filtration experiment is the spatial and temporal evolution of local porosity. A graphical presentation of this is shown in Figure 4a and is termed a porosity field map. From the porosity field map, three important characteristics of the filtration process can be obtained: the lower limit of the mixture zone, the upper limit of the mixture zone and the settlement line. The upper limit of the mixture zone is a result of the transport of base particles into the filter layer for upward seepage flow, while the lower limit of the mixture zone results from the concurrent settlement of the filter layer into the base layer. An outcome of overall mixing process in the settlement of the sample, which is defined by the settlement line. The porosity field maps provide a unique array of data from which a deeper understanding of the internal erosion mechanisms can be obtained.



(a) (b)

Figure 4: (a) Porosity field map data from coaxial permeameter cell. (b) Estimation of local permeability from spatial TDR data which is compared with conventional measures of permeability.

The initiation of filtration is clearly visible by the intersection of the lower and upper limits on the porosity field map, and the corresponding critical flow rate and hydraulic gradient can be readily determined. The critical flow rate showed a strong dependence on base particle size, with the critical flow rate increasing for larger base particles. In contrast, the critical hydraulic gradient exhibited a stronger dependence on the size of the filter particles, with a lower critical hydraulic gradient observed with increasing filter particle size. The continuation of filtration was also quantitatively captured in the porosity field map. A key observation was that the formation of the mixture zone was influenced by two mechanisms: (i) the transport of base particles into the filter layer due to upward seepage flows and (ii) the settlement of the filter particles into the base layer due to the reduction of the effective stress at the base–filter interface leading to partial bearing failure. Both mechanisms could be inferred from spatial TDR data by considering the differing gradients of the lower and upper limits of the mixture zones from the porosity field map. These gradients also provided quantitative insights into the continuation characteristics.

In addition to obtaining information on the local porosity, spatial TDR data can also be used to infer the local permeability. This was achieved by considering a variation on the well-known Kozeny-Carmen expression for permeability (Annapareddy et al., 2022), which incorporated the measured local porosity as well as an effective particle diameter that considered the fraction of finer and coarser particles. This enabled the local permeability measure to account for fines transport during filtration or suffusion experiments. A comparison of the local permeability obtained from spatial TDR (k_{local}^{TDR}) with the average permeability ($k_{average}$) and the local permeability obtained from pressure transducers (k_{local}^{PT}) is shown in Figure 4b. The average permeability remains constant within a layer, while the permeability obtained from pressure transducers remains constant between adjacent transducers. In contrast, the local permeability obtained from spatial TDR shows a near-continuous variation that is reflective of the inherent variability of the soil. Ongoing research is investigating the heterogeneity of the internal erosion process using this measure of local permeability.

4 CONCLUSIONS

This study presented the findings of particle-scale computational and physical experiments on internal erosion. Computational simulations of constant mean stress triaxial compression tests on gap-graded soils were conducted using the discrete element method and demonstrated that certain types of gap-graded soils may become more susceptible to suffusion when subject to anisotropic loading conditions. Physical experiments investigated the filtration process by conducting permeameter experiments using a purpose-built coaxial permeameter that utilised spatial time domain reflectometry to take near-continuous measurements of local porosity. These observations enabled the internal structure to be quantified from initiation to continuation to complete washout of particles. These particle-scale findings provide additional data that can improve the robustness and reliability of tools used by geotechnical engineers to assess the susceptibility to internal erosion, such as the piping toolbox. Moreover, developing a fundamental mechanics-based understanding can lead to the development of new techniques to investigate and assess internal erosion.

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