Microscale Investigations of Hydromechanical Failures of Granular Soils

by Shay Haq

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the degree of

Doctor of Philosophy

under the supervision of Distinguished Professor Buddhima Indraratna, Professor Cholachat Rujikiatkamjorn, and Dr. Thanh Nguyen

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Shay Haq, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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LIST OF NOTATIONS

α = stress reduction factor,

α_d = shape coefficient,

ΔP = pressure drop across the particle bed,

Δx = lattice spacing,

δ_n = normal overlap,

δ_t = tangential overlap,

$\dot{\varepsilon}$ = strain rate,

ε_a = axial strain,

ε_s = solid fraction in the fluid cell volume,

ε_v = volumetric strain,

γ_w = unit weight of water,

γ'= submerged unit weight of soil,

χ = safety factor coefficient,

$\varpi_{i,o}$ = weight factor,

ρ_f = fluid density,

Ω_α = collision operator,

${\Omega_\alpha}^{BGK}$ = collision operator of the BGK model,

${\Omega_\alpha}^{s}$= additional collision term for solid fraction,

μ_s= coefficient of sliding friction,

μ_f = dynamic viscosity of the fluid,

σ'_{ij} = Cauchy effective stress tensor in the selected region,

$\sigma^{p'}_{ij}$= average stress tensor within a particle p,

σ'_{zz} = Cauchy effective stresses of the particles in a layer in the fluid flow direction at any time, and

σ'_{zzo} = initial Cauchy effective stresses of the particles in a layer in the fluid flow direction**,**

τ = relaxation time,

B = weighing function to correct the collision phase due to the presence of solid particles,

B_R = percentage of broken contacts,

$C_{d,i}$ = drag coefficient of the fluid-particle system,

C_u = coefficient of uniformity value,

c_L = lattice speed,

c_n = viscoelastic damping constant for normal contact,

c_s = sound celerity,

c_t = viscoelastic damping constant for tangential contact,

D_{c35}^{c} = constriction size that is 35% finer by surface area in the CSD of the coarser fraction,

D_{c35}^{cl} = controlling constriction size at the loosest state,

D_{15}^{c} = particle size that is 15% finer by mass in the PSD of the coarser fraction,

d_p = diameter of the particle,

d_{avg} = average diameter of the coarser fraction of PSD,

d_{50} = particle size that is 50% finer by mass in the PSD,

d_{85} = particle size that is 85% finer by mass in the PSD,

d_{85}^{f} = particle size that is 85% finer by surface area in the finer fraction's PSD,

E^* = equivalent Young's modulus,

e_{α}^{v} = microscopic fluid velocity,

e_{oi}^{k} = initial void ratio of the k^{th} layer,

e_{oi}^{avg} = initial void ratio of the entire sample considering all 10 Layers,

e_r = coefficient of restitution,

F = finer particles' fraction at any particle diameter *D*,

$F_{d,i}$ = drag force,

$F_{\nabla p,i}$ = pressure gradient force,

$F_{\nabla \tau,i}$ = viscous force,

$F_{vm,i}$ = virtual mass force,

$F_{B,i}$ = Basset force,

$F_{Saff,i}$ = Saffman force,

$F_{mag,i}$ = Magnus force,

f_{bu} = static buoyancy force on the particle,

f_{hyd}^{p} = total hydrodynamic force (including the static buoyancy force) on the particle *p*,

f_f = hydrodynamic forces on the particle without buoyancy force,

f_g^p = gravitational force on the particle p,

f_j^c = force vector in *j^th^* direction at contact *c*,

f^T = tangential contact force,

f^N = normal contact force,

$f_\alpha(x, t)$ = particle distribution function,

$f_\alpha(x, t^*)$ = particle distribution function after the collision of fluid particles,

$f_\alpha^{eq}(x, t)$ = equilibrium distribution function,

G = shear modulus,

G^* = equivalent shear modulus,

H = incremental finer fraction between particle diameters *D* and *4D*,

I_n = Inertial number,

I^p = moment of inertia of the particle p,

i_o = overall applied hydraulic gradient,

$i_{o,cr}$ = critical overall hydraulic gradient of the soil specimen,

i_{hyd} = local hydraulic gradient in a layer,

k_n = elastic constant for normal contact,

k_t = elastic constant for tangential contact,

L = height of the particle bed,

M = Mach number,

M_s = fraction of mechanically stable particles,

m^p = mass of the particle p,

m^* = equivalent mass,

N = lattice resolution,

N_c = number of contacts,

N_d = number of degrees of freedom,

N_{ct} = number of constraints,

N_c^p = number of contacts on particle p,

$N_c^{coarse-coarse}$ = number coarse particle contacts,

$N_c^{fine-fine}$ = interparticle contacts of fine particles,

$N_c^{fine-coarse}$ = number of contacts between fine and coarse particles,

N_p = number of particles,

N_p^{coarse} = number of coarse particles,

$N_p^{\geq 4}$ = number of particles with at least 4 or more contacts,

n = overall porosity of the soil specimen,

n_c = skeleton's porosity,

$n_i^{c,p}$ = unit-normal vector from the centroid of the particle to the contact location,

n_L = number of layers,

O_i = initial centroidal location of particle i,

O_j = initial centroidal location of particle j,

O_j' = displaced centroidal location of particle j,

p^p = mean stress in the particle p,

p' = sample's effective mean stress equals the average of principal stresses,

p_f' = mean stress in the fines,

q = deviatoric stress,

R = constraint ratio for a three-dimensional particle system with only sliding resistance,

R_d = relative density,

R^* = equivalent radius,

Re_p = Reynold's number of the particle,

r_{min} = minimum particle radius,

S = variance in the void ratios,

S_i = slipping index,

S_c = fraction of slipping contacts,

T_f^p = fluid-particle interaction torque,

T_j^c = interparticle contact torque due to tangential force,

t = time,

t^* = time after the collision,

u = macroscopic fluid velocity,

$u_{f,o}$ = average fluid velocity of cell o,

$u_{p,i}$ = velocity of particle i residing in cell o,

u_{max} = maximum velocity of the fluid flow in physical units,

V = volume of the selected region or layer,

V^p = volume of particle p,

v_d = superficial or discharge velocity of the fluid,

v_f = kinematic viscosity of fluid,

v_n^{rel} = normal component of the relative velocity of two spherical particles,

v_t^{rel}= tangential component of the relative velocity of two spherical particles,

v^p = translational velocity of the particle p,

w^p = angular velocity of the particle p,

ω_α = weighing factor for the microscopic fluid velocity,

x^n = coordinate of the lattice cell,

x_i^c = location of the contact c,

x_i^p= centre of mass of the particle,

z = location of the particle,

Z = coordination number,

$Z^{fine-coarse}$ = fine-coarse coordination number,

$Z^{coarse-coarse}$ = coarse-coarse coordination number,

$Z_{avg.}$ = average coordination number,

LIST OF ABBREVIATIONS

ALE = Arbitrary Langrangian Eulerian,

BGK = Bhatnagar-Gross-Krook,

CF = Coarser Fraction,

CSD = Constriction Size Distribution,

CFD = Computational Fluid Dynamics,

DEM = Discrete Element Method,

DLM = Distributed Lagrange Multiplier,

DNS = Direct Numerical Simulations,

DSD = Deforming Spatial Domain,

FBM = Fictitious Boundary Method,

FD = Fictitious Domain,

FDM = Finite Difference Method,

FEM = Finite Element Method,

FF = Finer Fraction,

FVM = Finite Volume Method,

IBM = Immersed Boundary Method,

LAMMPS = Large-scale Atomic Molecular Massively Parallel Simulator,

LBM = Lattice Boltzmann Method,

LGA = Lattice Gas Automata,

LIGGGHTS = LAMMPS Improved for General Granular and Granular Heat Transfer Simulations,

MD = Molecular Dynamics,

MEM = Momentum Exchange Method,

NS = Navier-Stokes,

PCF = Pair Correlation Function,

PFC = Particle Flow Code,

PSD = Particle Size Distribution,

PSM = Partially Saturated Cells Method,

SA = Surface Area,

SST = Stabilised Space-Time,

USACE = United States Army Corps of Engineers,

μCT = Micro-Computed Tomography.

ABSTRACT

The Discrete Element Method (DEM) has proven useful to capture the micro and macro behaviour of soils. The complex micromechanical characteristics associated with hydromechanical failure of soils, such as internal instability and fluidisation, can be replicated with DEM. This research is divided into two parts, i.e., (i) microscale analysis of internal instability of cohesionless soils by using DEM under isotropic stress conditions and during shearing, and (ii) micromechanical analysis of fluidisation of granular soils by coupling DEM with the Lattice-Boltzmann Method (LBM).

Micromechanical analysis of the internal instability of cohesionless soils under isotropic stress state was carried out using DEM. The coordination number and the stress reduction factor were used to estimate the potential for internal instability of granular soils, and the clear boundaries between the samples that were internally stable and those that were unstable were delineated. Thereafter, the dense samples were sheared under drained conditions following a constant mean stress path to study the influence of shear deformation on internal instability. The simulation results showed that a dense sample could transition from internally stable to unstable soil as it dilates during shear.

Furthermore, microscale investigations on soil fluidisation were carried out using the DEM in combination with the LBM. The development of local hydraulic gradients, the distribution of contacts, and the associated fabric changes were examined. The microscale findings suggest that a critical hydromechanical state that induces fluid-like instability of a granular assembly can be described by a substantial and sudden increase in grain slippage combined with a decrease in interparticle contacts. Inspired by these results, a novel criterion is proposed to characterise the transformation of granular soil from a hydromechanically stable to a fluid-like state based on the constraint ratio, representing the relative slippage between the particles and the loss of contacts between the particles within the granular mass. The constraint ratio of unity corresponds to zero effective stress, representing the critical hydromechanical state.

Keywords: Internal Instability, Discrete Element Method, Coordination Number, Stress Reduction Factor, Fluidisation, Constriction Size Distribution, Lattice Boltzmann Method, Constraint Ratio, Critical Hydraulic Gradient