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Incorporating suction effects into DEM modelling of granular soils

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Unsaturated soils are ubiquitous in geotechnical engineering applications, yet their behaviour is challenging to study through conventional laboratory experiments due to the complexity and cost associated with testing in unsaturated conditions. Discrete Element Method (DEM) simulations offer an alternative approach for investigating the behaviour of unsaturated granular soils. However, current methods for incorporating suction effects into DEM models are often overly complex, rendering them impractical or heavily reliant on the assumption of spherical particles, which compromises accuracy for non-spherical grains. This study proposes a simple, yet reasonably accurate framework to incorporate suction effects into DEM simulations, addressing these limitations. By coupling DEM with a Pore Network Model (PNM), the approach accounts for pore water distribution within the soil matrix to compute capillary forces between particles. The coupled DEM-PNM framework enables a comprehensive analysis of the interactions among soil particles, pore water, and air under unsaturated conditions, allowing for the simulation of granular soil behaviour across a wide range of saturation levels. The validity of the proposed method is demonstrated through comparisons with laboratory observations, and its practical applications are illustrated through case examples. The proposed approach enhances the understanding of the behaviour of granular materials in unsaturated conditions.

KEYWORDS: Discrete element method, Pore network model, Unsaturated soil, Suction.

1 INTRODUCTION

The hydro-mechanical behaviour of unsaturated granular soils governs the performance of a wide range of geotechnical and geo-environmental systems, including slopes, foundations, pavements, retaining walls, and landfill covers. In arid and semi-arid regions, where soils are rarely fully saturated, the variation of suction and water content significantly influences their strength, deformation, and stability. Unlike saturated soils, where pore water pressure is uniformly distributed, partially saturated soils exhibit discrete liquid bridges at particle contacts. These menisci generate capillary forces whose magnitude and distribution vary with suction and degree of saturation, producing highly nonlinear and sometimes non-monotonic shear strength responses.

Experimental characterisation of unsaturated soils, typically via suction-controlled triaxial tests, is both time-consuming and resource-intensive, and provides limited insight into particle-scale mechanisms. The Discrete Element Method (DEM) offers a complementary tool, enabling explicit simulation of particle interactions, force transmission, and fabric evolution under coupled hydraulic–mechanical loading. In the context of unsaturated soils, DEM has been utilised to capture capillary forces through the introduction of water bridges between particles. To accurately capture the behaviour of partially saturated soils using DEM, it is essential to simulate the pore-scale water distribution. However, most DEM-based models have been confined to the pendular regime ($S_r < 15\%$), where water exists as isolated menisci between neighbouring particles (Richefeu et al. 2009). Extensions of DEM to higher saturation ranges have often included the adoption of empirical adhesive bonds, pendular bridge approximations, and lattice-Boltzmann couplings. Although methods such as the 2PFV-DEM framework (Yuan & Chareyre 2017) and DEM–LBM coupling (Younes et al. 2023) have improved physical representation, they remain limited due to their high computational demands or inability to model isolated liquid bridges. Liu et al. (2020) proposed an advanced model that explicitly incorporates water–solid interface morphologies across regimes, but the method requires computationally expensive geometric discretisation.

An alternative approach is to couple DEM with Pore Network Modelling (PNM), whereby a DEM-generated granular assembly is post-processed to extract pore–throat geometry, enabling efficient simulation of drainage/imbibition and capillary pressure–saturation behaviour. Existing DEM–PNM approaches, however, often rely on simplified pore geometries or averaged throat radii, neglecting explicit water–soil interfacial area calculations critical for accurate capillary force estimation.

To address these gaps, this study develops a coupled DEM–PNM framework capable of simulating unsaturated soil behaviour across the full saturation spectrum. The approach computes capillary forces directly from the measured water–soil surface area at each suction, derived from the actual pore network topology. These forces are integrated with contact forces in DEM to resolve the net particle-scale interactions under mechanical loading. The model enables detailed investigation of micro–macro linkages, including the role of interfacial area in effective stress and the evolution of force networks under varying suctions.

The proposed method is validated against suction-controlled triaxial tests on silty sand, demonstrating its ability to reproduce non-monotonic shear strength trends and volumetric behaviour. Furthermore, the model facilitates the derivation of a physically based effective stress parameter χ from capillary stress distributions for silty sands.

2 METHODOLOGY

This study extends the coupled DEM–PNM framework developed in Mahboobi Motlagh et al. (2025) to integrate capillary forces based on evolving water–soil interfacial areas. Granular assemblies representative of target silty sand grain size distributions were generated in PFC^{3D} (Version 7, Itasca Consulting Group, 2023). Particles were allowed to settle under gravity within a cylindrical mould until mechanical equilibrium was reached, followed by isotropic loading to achieve the target void ratio.

Once stabilised, the pore network was extracted using regular triangulation (Delaunay tessellation). Pore bodies were defined as free space in tetrahedra formed by four particle centres, and throats as the shared facets between adjacent tetrahedra. Water retention under drainage and imbibition was simulated by applying the Young–Laplace equation to determine the entry/exit pressure of each throat.

The proposed approach advances prior work by coupling capillary forces, directly computed from the actual water–soil interfacial area, into the DEM environment. The simulation procedure comprised six stages: 1) DEM generation of a granular assembly to match target grain size distribution and void ratio, 2) Pore–throat network extraction via PNM, 3) Simulation of suction-controlled drainage using a pore invasion algorithm, 4) Calculation of capillary forces from water–soil interface area, 5) Integration of capillary and contact forces in DEM, and 6) Analysis of suction effects on mechanical behaviour of unsaturated materials.

The calculation of capillary forces requires an accurate estimation of the water–soil interfacial area, which depends on the spatial distribution of pore water in the soil matrix. The following presents a simplified, yet effective, approach to estimate this interfacial area. Initially, a fully saturated state was assumed, with the interfacial area at a contact approximated by the contact area of the smaller particle:

$$A_s = \pi r_{p,min}^2 \qquad (1)$$

where $r_{p,min}^2$ is the radius of the smaller particle at the contact. Drainage was simulated incrementally by increasing suction, identifying throats with radii exceeding the capillary radius defined by the Young–Laplace equation. Invaded throats and connected pores were assigned to the non-wetting phase, updating water distribution and degree of saturation. The reduction in wetted area was quantified using a scaling factor:

$$\beta = \frac{\sum_{i=1}^{N_1} r_{throat,i}^2}{\sum_{i=1}^{N} r_{throat,i}^2} \qquad (2)$$

where N is the total number of throats around a particle in the fully saturated state, N_1 is the number of throats that the non-wetting phase has not invaded, and r_{throat} denotes the effective radius of each throat (Bryant and Blunt 1992). Capillary forces were scaled proportionally to β at each suction step.

In the simulations, the total force applied to a soil particle, F_{total}, is a combination of the forces caused by the fluid, F_{cap} and the mechanical inter-particle contact forces (F_{cont}). At each stage, DEM computed the total particle force as:

$$F_{total} = F_{cap} + F_{cont} \qquad (3)$$

Contact forces followed a linear contact law (Cundall & Strack 1979). Particle motion was updated using Newton's second law, enabling prediction of stress–strain and volumetric responses.

This integrated DEM–PNM framework robustly and efficiently links pore-scale drainage processes to particle-scale force transmission, allowing physically informed simulation of unsaturated soil behaviour across the full suction spectrum.

3 VERIFICATION OF THE PROPOSED DEM–PNM MODEL

The predictive capability of the proposed coupled DEM–PNM for simulating the hydro-mechanical behaviour of unsaturated soils was verified through direct comparison with the results reported by Liu et al. (2020). The reference study employed a rigorously validated micro-mechanical framework incorporating an explicit representation of liquid–solid interfaces and capillary forces, thereby providing a robust basis for validation.

A dense silty soil assembly was generated in the present study following the particle size distribution adopted by Liu et al. (2020), comprising spherical particles with diameters ranging from 11.7 µm to 34.5 µm. The assembly contained 20,258 particles confined between rigid, frictionless plates and flexible lateral boundaries. After isotropic compaction to a confining stress of 80 kPa, the assembly attained a void ratio of 0.66. The interparticle friction coefficient was set to $\mu = 0.5$ for all simulations, consistent with the benchmark study. Model parameters are summarised in Table 1.

Table 1. DEM simulation parameters.

Parameters	Symbol	Values
Particle density	ρ	2710 kg/m^3
Contact stiffness of the wall	K_{wall}	1 MN/m
Normal to shear contact stiffness	k_n/k_s	1.5
Particle Young's modulus	E_p	70 GPa
Local damping	α	0.7

Verification was performed for both hydraulic and mechanical responses. For the hydraulic response, suction–degree of saturation relationships (i.e., soil–water retention curves, SWRCs) predicted by the proposed model were compared with those obtained using the revised pore morphology approach of Liu et al. (2020). As shown in Figure 1, the SWRCs exhibit excellent agreement, with both models yielding identical air-entry (~ 20 kPa) and residual suction (~ 70 kPa) values. The proposed model successfully reproduced the transitions between pendular, funicular, and capillary regimes, confirming its physical consistency in representing pore-scale water distribution and associated capillary effects.

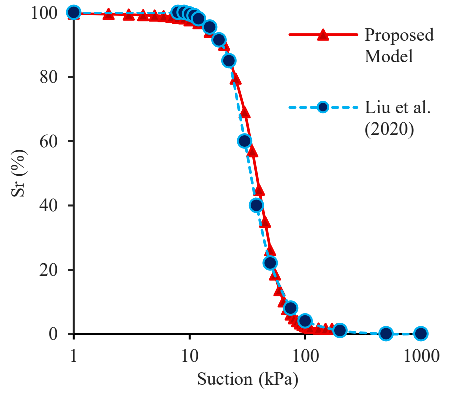
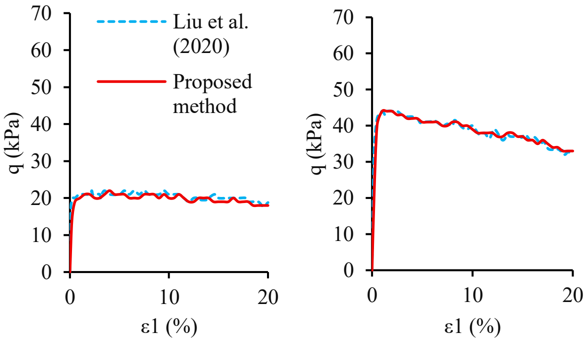
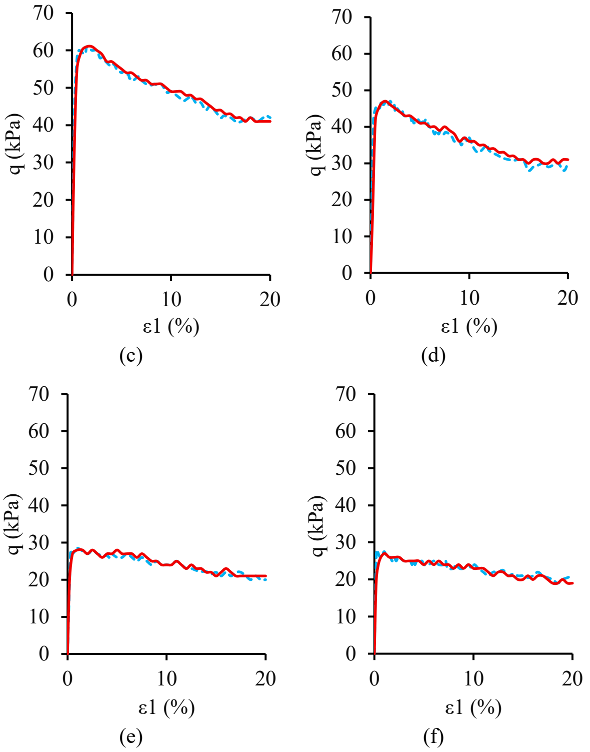


Figure 1. SWRCs derived from the proposed model and Liu et al.'s model.

For the mechanical response, triaxial compression tests under suction-controlled conditions were simulated at a confining pressure of 10 kPa for suctions ranging from 0 kPa to 100 kPa. The deviator stress–strain and volumetric strain–strain responses (Figures 2–3) closely matched those reported by Liu et al. (2020), capturing the observed trends of peak strength, post-peak strain softening, and dilation. Both datasets showed that peak and critical strengths increased with suction up to ~ 40 kPa (funicular regime), followed by a reduction in strength and dilation at higher suctions, consistent with the established role of capillary cohesion (Schubert 1984; Lu et al. 2009).



(a) (b)

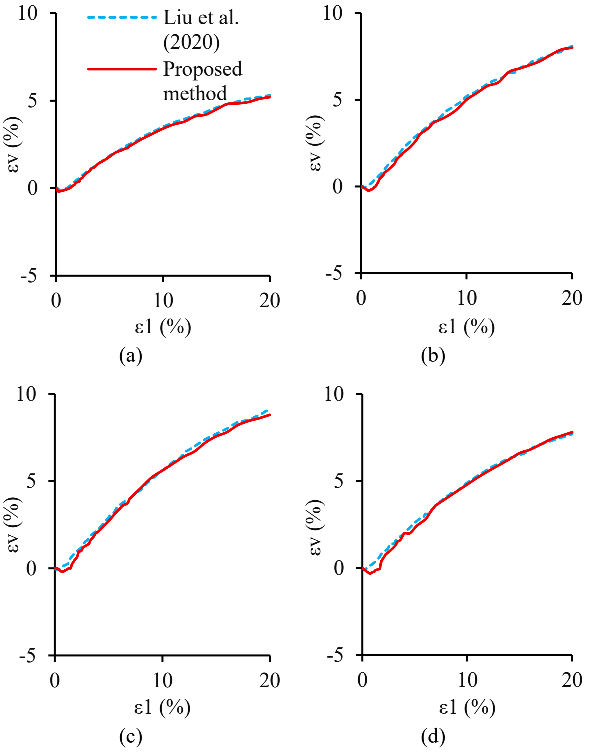


(c) (d)

(e) (f)

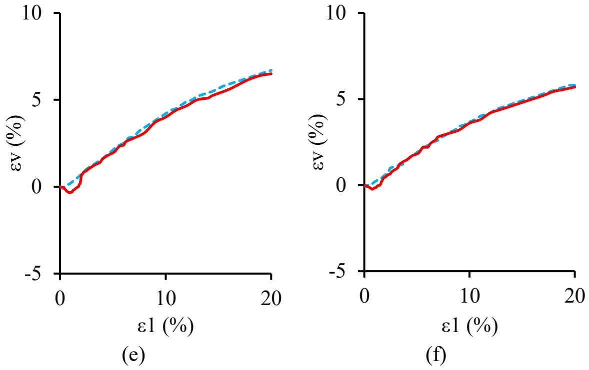
Figure 2. Evolution of deviator stress as a function of axial strain under a confining pressure of 10 kPa for (a) s=0, (b) s=20 kPa, (c) s=40 kPa, (d) s=60 kPa, (e) s=80 kPa, and (f) s=100 kPa.

Overall, the close agreement between the present and benchmark results for SWRCs, stress–strain behaviour, and volumetric responses across a wide range of suctions demonstrates that the proposed DEM–PNM approach reliably captures the coupled hydro-mechanical response of unsaturated soils.



(a) (b)

(c) (d)



(e) (f)

Figure 3. Evolution of volumetric strain as a function of axial strain under a confining pressure of 10 kPa for (a) s=0, (b) s=20 kPa, (c) s=40 kPa, (d) s=60 kPa, (e) s=80 kPa, and (f) s=100 kPa.

4 APPLICATION

The application of the model for estimating the effective stress parameter is demonstrated in this section. A series of triaxial tests were simulated under a uniform net confining stress of 10 kPa, with degrees of saturation ranging from dry to fully saturated conditions. Following consolidation, the radial internal contact stresses (σ'), arising from particle–particle and particle–wall interactions, were obtained. For saturated and dry specimens, the contact stresses closely matched the applied net stress of 10 kPa, as expected. In contrast, for partially saturated specimens, the measured contact stresses deviated from the applied stress, consistent with the expectation that suction in unsaturated conditions alters the contact stress.

The effective stress parameter, χ, was then evaluated for various suction levels using the Donald (1956) and Bishop (1961) formulation,

$$\sigma' = \sigma_{net} + \chi s \tag{4}$$

The variation of resulting χ values with degree of saturation is plotted in Figure 4 and compared with the corresponding data reported by Liu et al. (2020).

The results reveal strong agreement across the full range of saturation. Notably, Liu's data exhibit a slight underestimation of χ relative to the $\chi = S_r$ line at low saturation levels, and a slight overestimation at intermediate and high saturations, a trend also mirrored by the present model.

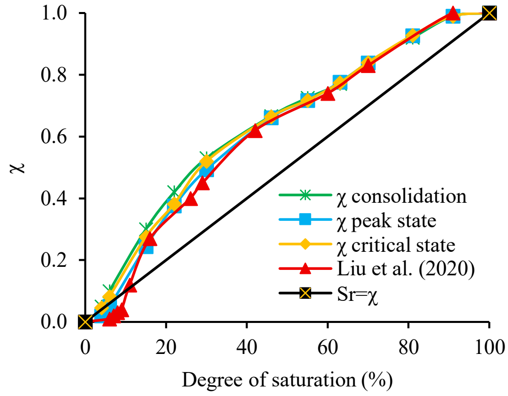


Figure 4. Comparisons between the results with the effective stress parameter χ predicted by Liu et al. (2020) and the proposed model for end of consolidation, peak, and critical states.

The simulation results over the ascending portion of the shear strength–suction curve (20–45 kPa suction) were then used to back-calculate χ for the simulated soil. Figure 5 presents the variation of the back-calculated χ with the ratio of air-entry pressure to suction (s_e/s). As shown, the simulated results can be fitted with a power-law function exhibiting a coefficient of determination of 0.99. The power of the function is 0.55, which is notably identical to the best-fit value of χ proposed by Khalili and Khabbaz (1998).

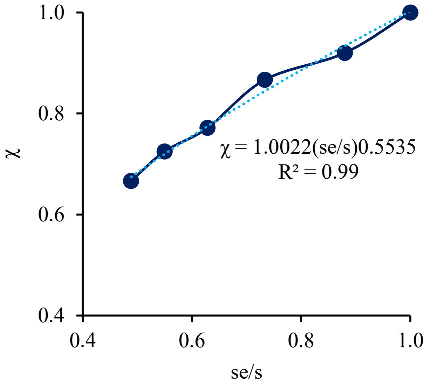


Figure 5. The variation of the effective stress parameter χ derived from DEM simulations with $\frac{s_e}{s}$.

These findings demonstrate the applicability of the proposed model in simulating unsaturated soil behaviour and further confirm the capability of the DEM–PNM framework to capture suction-dependent variations in effective stress and shear strength, as well as to reproduce established empirical correlations for estimating the effective stress in unsaturated soils.

5 CONCLUSION

This study presented a coupled Discrete Element Method–Pore Network Modelling (DEM–PNM) framework for simulating the hydro-mechanical behaviour of unsaturated granular soils across the full saturation spectrum. The approach integrates capillary forces, computed directly from the evolving water–soil interfacial area extracted from the actual pore–throat geometry, into DEM, enabling a physically consistent representation of particle-scale interactions under varying suctions.

Validation against benchmark simulations demonstrated excellent agreement in soil–water retention curves (SWRCs), deviatoric stress–strain responses, and volumetric strain evolution. The proposed model accurately reproduced the key hydraulic and mechanical features of unsaturated soils, including the transitions between pendular, funicular, and capillary regimes. The application of the model is demonstrated through the back-calculation of the effective stress parameter, χ. The results exhibited remarkable consistency with the formulation proposed by Khalili and Khabbaz (1998) over the funicular suction range, reinforcing its applicability for capturing suction–strength correlations in this range. This outcome underscores the capability of the model to unify micro-scale capillary stress computations with macro-scale effective stress formulations. The proposed DEM–PNM framework provides a computationally efficient and physically grounded tool for exploring micro–macro mechanisms in unsaturated soil behaviour.

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