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PARTICLE SCALE ANALYSIS OF THE IMPACT OF PARTIAL DRAINAGE ON UNDRAINED SHEAR RESPONSE APPLIED TO DESATURATION

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Abstract: The devastating consequences of liquefaction-driven failures have made mitigation and prevention an active focus of research. Soil desaturation can mitigate liquefaction by incorporating gas bubbles into saturated soil. This study uses the discrete element method (DEM) to investigate the mechanisms and to explore the fundamental basis of mitigation approaches based upon desaturation. Spherical assemblies are isotropically compressed and then subjected to three types of triaxial shearing: (i) fully drained, (ii) fully undrained, and (iii) partially drained. The observed stress responses indicate that classical liquefaction phenomena can be observed even when the constant volume condition is relaxed. However, a slight reduction in the constant volume restraint is sufficient to maintain a statically determinate soil structure, supporting the case for soil desaturation to mitigate liquefaction.

1. Introduction

Static and earthquake-induced liquefaction can have devastating economic and societal impacts. Previous studies (e.g. [1]) have demonstrated that the discrete element method (DEM) can recreate undrained conditions by restricting the deformation of the spherical assembly to achieve a constant volume. In this way liquefaction can be simulated using DEM without explicitly considering the water phase. Element test simulations using DEM can facilitate useful parametric studies to advance understanding of macro-scale (i.e. continuum) soil behavior, while also providing a rich set of data which can be used to inform fundamental understanding at particle level. Soil desaturation, in which there is a small reduction in the in-situ degree of saturation, is one potential approach to mitigate liquefaction risk in situ [2]. The method increases the compressibility of the pore fluid by incorporating gas bubbles into the saturated soil either by chemical or bio-induced means (e.g. [3], [4]). The novelty and potential of this technique have attracted researchers to experimentally test its efficiency (e.g. [5]), however, studies focused on the micro-mechanics of this process remain scarce. This study builds upon prior numerical and experimental work (e.g. [6], [7]) and uses DEM to explore the fundamental basis for this approach and advance understanding of the fundamental mechanisms that lead to liquefaction under constant volume and partially drained deformation, applied to desaturation.

2. Methodology

The DEM simulations were run using the open-source molecular dynamics code LAMMPS [8]. The virtual samples comprised 4,954 spherical particles with a particle size distribution (PSD) corresponding to Toyoura sand [9]. Periodic boundaries were employed in all directions, and a simplified Hertz-Mindlin contact model was adopted to calculate inter-particle normal and tangential forces as a function of particle overlap and shear history. The particle density, ρ_s , corresponds to the density of quartz (2670 kg/m^3), scaled by a factor of 10 to reduce the computational cost. The numerical stability of the simulations was ensured by adopting a conservative timestep, Δt , following [10]. A summary of the DEM simulation parameters is presented in Table 1.

Particles were randomly placed on a cubical box and then isotropically compressed to a target confining pressure of $\sigma'_c = 300 \text{ kPa}$. A relatively loose packing with a void ratio of $e = 0.6308$ was attained by setting the inter-particle friction coefficient to $\mu = 0.25$. Following the definition of [11]



Parameter	Value	Units	Parameter	Value	Units
Shear modulus, G	1.0	GPa	Interparticle friction, μ	0.25	-
Poisson's ratio, ν	0.12	-	Local damping, η	0.1	-
Particle density, ρ_s	2.67×10^{-4}	kg/m^3	Timestep, Δt	8.88×10^{-8}	s

Table 1. DEM simulation parameters.

and considering the critical state line in [12], the initial state parameter of the sample, ψ , was estimated as 0.019. After the isotropic compression phase, the sample was subjected to monotonic triaxial shearing by vertically compressing the samples with a constant strain rate of $\dot{\epsilon}_z = 0.17$ 1/s. Samples were sheared to an 18% of axial strain, ϵ_z . The inertial number, I , was estimated as 2.8×10^{-6} , which is below the quasi-static limit usually adopted in DEM simulations [13].

Three different types of triaxial shearing were considered here: (i) a fully drained (constant σ'_3), (ii) a constant volume (fully undrained), and (iii) an intermediate scenario where a fraction β of the volumetric of the drained volumetric strain was applied to the sample. Two β values were evaluated: $\beta = 0.05$, and 0.25 . Condition (iii) was achieved via a control algorithm which imposed a volumetric strain, ϵ_{vol} at each increment of axial strain (ϵ_z). The values of ϵ_{vol} were specified as a proportion ($\beta = 0.05$ or 0.25) of the drained volumetric strain, ϵ_{vol}^{DR} , at the same axial strain, i.e. $\epsilon_{vol}^\beta = \beta \epsilon_{vol}^{DR}$ where $0 \leq \beta \leq 1$ is a dimensionless constant. This algorithm is a generalization of the strain-controlled linear path tests found in the DEM literature (e.g. [6]). The parameters involved in the control algorithm were then calibrated against the data from the fully drained simulations.

Under the assumption of a discontinuous air phase, the dimensionless constant, β , can be interpreted as an indirect controller of the compressibility of the equivalent mixture of air and water. The addition of air bubbles into the pore space and their collapse during shearing can lead to an enhanced contraction or a reduction in the deformation modulus [14]. Recalling the definition of bulk modulus of the soil skeleton, K_s , and applying the chain rule over $dp'/d\epsilon_{vol}$ it can be shown that the introduction of β results equivalent to a reduction in the bulk modulus of the sample, i.e., $K^\beta \sim \beta K^{DR}$. Moreover, β values lesser than unity are reflected in a reduction in Skempton's B parameter [15], commonly employed to assess the saturation level in laboratory tests.

3. Macro and Micromechanical Response

Figure 1(a) gives the simulation results in terms of the stress path observed. The undrained sample and the samples with $\beta = 0.05$ and 0.25 exhibit classical features associated with static liquefaction. From the onset of shear deformation, the mean effective stress, p' , decreases. Initially, the deviator stress, $q = \sigma_1 - \sigma_3$, increases to a peak value, then it decreases to a local minimum value at the phase transformation point (diamond markers, labelled as PT), and then there is a subsequent increase in q . It is only in the case of the fully undrained (constant volume) simulation that q reduces to zero. Figure 1(b) shows the variation of the volumetric strain, ϵ_{vol} , as a function of the axial strain of the sample. Results from both figures indicate an increase of q with β , which means that the contraction imposed on the sample is reflected in an increment of stresses.

Figure 2(a) illustrates the variation in the coordination number, Z , (average number of contacts per particle) as a function of axial strain. Interestingly, it is only in the fully undrained case that Z falls beneath the value of 4 which is the minimum Z value for a statically indeterminate system [16]. In contrast to the fully drained case where there is an initial slight increase in Z , for $\beta = 0.05$ and $\beta = 0.25$ there is a clear reduction in Z from the start of shearing, however Z remains above 4.5.

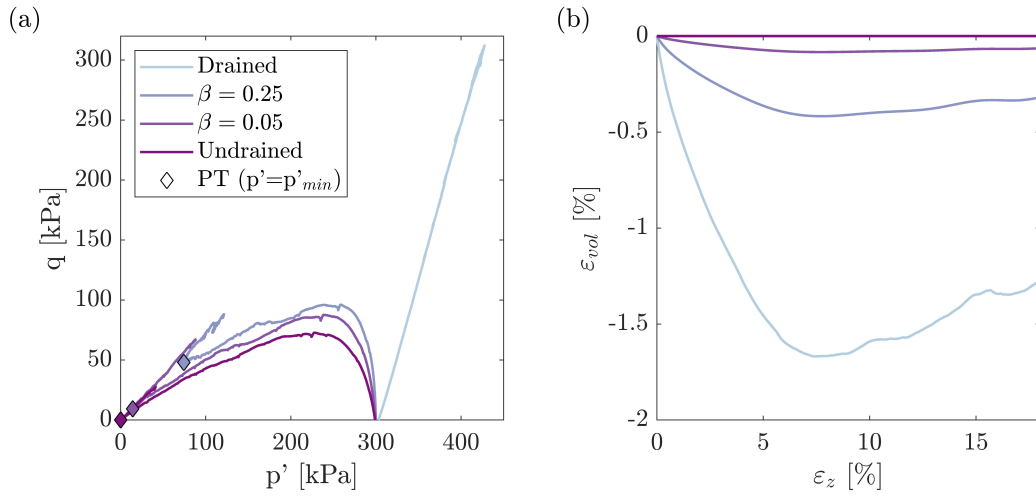


Figure 1. Observed response in triaxial shear (a) Deviator stress versus mean effective stress and (b) volumetric strain versus axial strain.

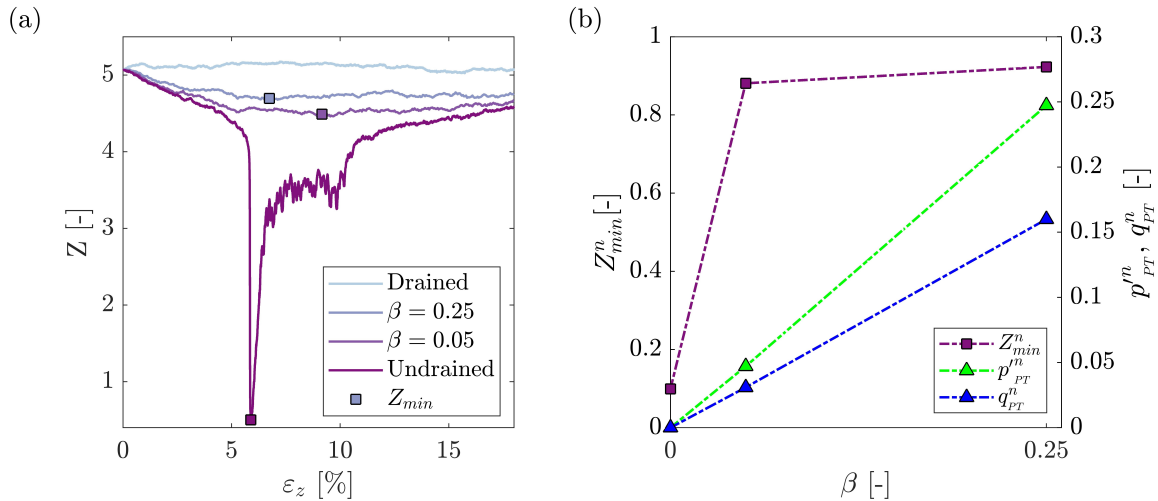


Figure 2. Observed response in triaxial shear (a) Coordination number (Z) versus axial strain and (b) normalized coordination number and phase transformation invariants (p' and q) versus β .

To assess if there is a systematic variation in the stress response and the coordination numbers with β , Figure 2(b) shows the evolution of the normalized minimum coordination number, i.e. $Z_{min}^n = Z_{min}/Z_0$, the normalized mean effective stress at the PT point, i.e. $p_{PT}^n = p'_{PT}/p'_0$, and the normalized deviatoric stress at the PT point, i.e. $q_{PT}^n = q_{PT}/p'_0$, where $Z_0 = 5.2$ and $p'_0 = 300$ kPa. Whereas a linear trend is observed for both normalized stress indicators (p_{PT}^n and q_{PT}^n), a sharp early increase and a subsequent plateau is observed for Z_{min}^n . The different trends depicted in Figure 2(b) suggest that only a small volumetric contraction or desaturation level is required to rebuild most of the contacts lost due to a liquefied condition. The data also indicate that the recovery in the number of contacts is not proportionally reflected in a gain of strength (in terms of q), suggesting that most of the recovered

contacts are not involved in strong force chains (contrary to drained shearing). Further simulations and analyses are required to confirm or discard these hypotheses.

4. Conclusions

An algorithm was employed to control the volumetric strain during triaxial shear deformation in DEM simulations through the introduction of an adimensional constant, β , here interpreted as an indirect controller of the compressibility of the equivalent mixture. At the macro-scale, the resulting data show that classical liquefaction phenomena can be observed for the small amounts of volumetric contraction considered here ($\beta \leq 0.25$). As might reasonably be expected, the coordination number, Z is sensitive to β . A small volumetric contraction ($\beta = 0.05$) is sufficient to maintain a statically determined soil structure ($Z \geq 4$). Further examination of these data may provide insight into the phenomenon of soil liquefaction, how it is influenced by soil desaturation, and to confirm or discard the hypothesis herein proposed. A key challenge is to extend this approach to consider cyclic loading.

References

- [1] Ng, T.-T. and Dobry, R. (1994). Numerical simulations of monotonic and cyclic loading of granular soil. *Journal of Geotechnical Engineering*, **120**, 388–403.
- [2] Seyedi-Viand, S. M. and Eseller-Bayat, E. E. (2022). Partial saturation as a liquefaction countermeasure: a review. *Geotechnical and Geological Engineering*, pp. 1–32.
- [3] Moug, D. M., et al. (2022). Field trials of microbially induced desaturation in low-plasticity silt. *Journal of Geotechnical and Geoenvironmental Engineering*, **148**, 05022005.
- [4] Mele, L., Tian, J. T., Lirer, S., Flora, A., and Koseki, J. (2019). Liquefaction resistance of unsaturated sands: experimental evidence and theoretical interpretation. *Géotechnique*, **69**, 541–553.
- [5] Okamura, M. and Soga, Y. (2006). Effects of pore fluid compressibility on liquefaction resistance of partially saturated sand. *Soils and Foundations*, **46**, 695–700.
- [6] Nicot, F., Daouadji, A., Hadda, N., Jrad, M., and Darve, F. (2013). Granular media failure along triaxial proportional strain paths. *European Journal of Environmental and Civil Engineering*, **17**, 777–790.
- [7] Nakata, Y., Tashita, T., Chibana, H., and Matsukata, K. (2019). Effect of drainage and saturation on undrained shear strength for compacted sandy soils. *E3S Web of Conferences*, vol. 92, p. 07003, EDP Sciences.
- [8] Thompson, A., et al. (2022). Lammmps-a flexible simulation tool for particle-based materials modeling at the atomic, meso, and continuum scales. *Computer Physics Communications*, **271**.
- [9] Yang, J. and Sze, H. (2011). Cyclic behaviour and resistance of saturated sand under non-symmetrical loading conditions. *Géotechnique*, **61**, 59–73.
- [10] Otsubo, M., O’Sullivan, C., and Shire, T. (2017). Empirical assessment of the critical time increment in explicit particulate discrete element method simulations. *Computers and Geotechnics*, **86**, 67–79.
- [11] Been, K. and Jefferies, M. G. (1985). A state parameter for sands. *Géotechnique*, **35**, 99–112.
- [12] Huang, X., O’Sullivan, C., Hanley, K., and Kwok, C. (2014). Discrete-element method analysis of the state parameter. *Géotechnique*, **64**, 954–965.
- [13] Shire, T., Hanley, K. J., and Stratford, K. (2021). Dem simulations of polydisperse media: efficient contact detection applied to investigate the quasi-static limit. *Computational Particle Mechanics*, **8**, 653–663.
- [14] Wheeler, S. (1986). *The stress-strain behaviour of soils containing gas bubbles*. Ph.D. thesis, University of Oxford.
- [15] Skempton, A. (1954). The pore-pressure coefficients a and b . *Geotechnique*, **4**, 143–147.
- [16] O’Sullivan, C. (2011). Particle-based discrete element modeling: geomechanics perspective. *International Journal of Geomechanics*, **11**, 449–464.