Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-214

Particle size distribution induced fabric effects on the onset and post liquefaction behaviours of soils

La distribution granulométrique induit des effets de tissu sur le comportement initial et post-liquéfaction des sols

J. Leak*, D. Barreto
Edinburgh Napier University, School of Computing Engineering and the Built Environment, Edinburgh

**J.leak@napier.ac.uk*

ABSTRACT: Liquefaction in soils is a detrimental phenomenon. Microscale behaviours and their influence on the macroscale response during and after the onset of liquefaction are not well understood. In particular, how contact behaviours effect macroscale properties such as gains in shear strength following the onset of liquefaction. Soil characteristics such as particle size distribution (PSD) are known to have important roles in determining a soils susceptibility to liquefaction. In this study, Discrete Element Simulations (DEM) are undertaken on soils with different PSDs to investigate how contacts at the microscale are influenced by PSD and how this influences the macroscale response. Consideration is given to these behaviours before and after the onset of liquefaction to gain insight into post-liquefaction strength behaviour. Using grading entropy coordinates, it is suggested that the PSD plays a key role in a soils ability to resist liquefaction. Larger grains appear to provide greater stability and an ability gain interparticle contacts post-liquefaction. This greater stability is suggested to come from the grain structure resisting being broken and remade during liquefaction, manifesting in greater isotropy throughout loading. Whereas soils with smaller PSDs are more prone to having their grain structure broken and remade, enabling them to become significantly more anisotropic, this appears to inhibit the ability to regain interparticle contacts.

RÉSUMÉ: La liquéfaction des sols est un phénomène néfaste. Les comportements à l'échelle microscopique et leur influence sur la réponse à l'échelle macro pendant et après le début de la liquéfaction ne sont pas bien compris. En particulier, comment les comportements de contact affectent les propriétés à l'échelle macro, telles que les gains de résistance au cisaillement après le début de la liquéfaction. Les caractéristiques du sol telles que la distribution granulométrique (PSD) sont connues pour jouer un rôle important dans la détermination de la susceptibilité des sols à la liquéfaction. Dans cette étude, des simulations d'éléments discrets (DEM) sont entreprises sur des sols présentant différentes PSD pour étudier comment les contacts à l'échelle microscopique sont influencés par la PSD et comment cela influence la réponse à l'échelle macro. Ces comportements sont pris en compte avant et après le début de la liquéfaction afin de mieux comprendre le comportement en matière de résistance après liquéfaction. En utilisant les coordonnées entropiques de gradation, il est suggéré que la PSD joue un rôle clé dans la capacité des sols à résister à la liquéfaction. Les grains plus gros semblent offrir une plus grande stabilité et une capacité à gagner des contacts interparticulaires après liquéfaction. Il est suggéré que cette plus grande stabilité provienne du fait que la structure des grains résiste à la rupture et à la reconstruction lors de la liquéfaction, se manifestant par une plus grande isotropie tout au long du chargement. Alors que les sols avec des PSD plus petits sont plus susceptibles de voir leur structure granulaire brisée et refaite, ce qui leur permet de devenir significativement plus anisotropes, cela semble inhiber la capacité à retrouver les contacts interparticulaires.

Keywords: Liquefaction; particle size distribution; grading entropy; soil fabric.

1 INTRODUCTION

Susceptibility to liquefaction can be determined with reference to a soils particle size distribution (PSD). Regarding this approach several methods have been proposed (e.g. Tsushida & Hayashi, 1971). The abundance of PSD based susceptibility criteria clearly indicate that a relationship exists between the initiation of liquefaction and grain size. Barreto et. al. (2019) assessed different susceptibly criteria using the grading entropy method proposed by Lőrincz (1986). This study affirmed a clear relationship between the entire PSD (i.e. including fines and gravel content) and liquefaction susceptibility, with reference to the grading entropy stability criteria. Moreover, the study highlighted the benefits of the grading entropy coordinates as a PSD based susceptibility criteria.

There is evidence to suggest that a relationship between PSD and increases in post-liquefaction shear strength exist also. Whilst aspects such as confining stress, void ratio or relative density, fines content etc, are highly influential, PSD appears to be an important factor in the initiation of liquefaction and its ability to regain its strength following failure, via rebuilding interparticle contacts. It was discussed by Manmatharajan et al. (2023), that amongst varying PSDs, coarser well-graded PSDs showed greater post-liquefaction shear strength, particularly when compared to PSDs with the presence of fines, and poorly graded soils.

It has also been suggested that post-liquefaction shear strength may in part also be related to the orientation in particle fabric. For example, Wang et al (2020) investigated the post liquefaction shearing resistance of gravelly soils and found that the more anisotropic a soil is, the greater the difficulty it exhibits rebuilding shear strength and stable inter-particle particle contacts – leaving the soil vulnerable to secondary liquefaction. This was something also suggested by Otsubo et al. (2022), who stated that soils with a greater inherent isotropic fabric may have the potential to exhibit greater liquefaction resistance.

This study investigates the effect of PSD on the initiation and post-liquefaction contact behaviours of soils. Emphasis is placed on the influence of PSD and fabric behaviours, and exploring the role this plays in the development of liquefaction and a soils ability to regain interparticle contacts following failure. In this work, the entire PSD is assessed using grading entropy coordinates, enabling for the entire PSD to be represented.

2 GRADING ENTORPY

Proposed by Lőrincz (1986), grading entropy condenses the entirety of a PSD to a single point on a Cartesian plane. This is achieved by accumulating the information entropy within each soil fraction to ascertain the total grading curve entropy. The total grading entropy can then be split into two components which form a coordinate pair:

$$S = \Delta S + S_0 \tag{1}$$

where S is the total grading entropy, ΔS is the entropy increment, typically on the y-axis, and S_0 is the base entropy typically on the x-axis. The base entropy (S_0) is a logarithmic mean of the average grain diameter relating to the skewness of the PSD. ΔS is a measure of how much a PSD is influenced by all its fractions and relates to the kurtosis of the PSD.

ΔS and S_0 have normalised counterparts, where $0<A<1$ and $0<B<B_{max}$ 1.41. A is the normalised base entropy and B is the normalised entropy increment, given by:

$$A = \frac{S_0 - S_{0min}}{S_{0max} - S_{0min}} \tag{2}$$

$$B = \frac{\Delta S}{\ln(N)} \tag{3}$$

where N is the number of sieve fractions in the PSD. Whilst grading entropy coordinates may be related to commonly used descriptors, it should be noted that in contrast to these, ΔS, S_0 and A, B involve information about the entire PSD, not just specific particles diameters (e.g., d_{10}, d_{30}, $d_{50,}$ d_{60}) and enables for the direct consideration of both fines and gravel content with no need for additional descriptors. In this study, only the normalised coordinates are used.

3 DEM SIMULATIONS & PSDs

Undrained monotonic DEM simulations were performed using the open-source software YADE. Specimens were randomly generated within cubical periodic boundaries and isotropically compressed prior to triaxial loading under constant volume conditions. A summary of the DEM input parameters is shown in Table 1.

Table 1. DEM Input parameters.

Description	Value
Confining Stress	200 kPa
Poisson's ratio (ν)	0.22
Particle density (ρ)	2650 kg/m^3
Inter-particle friction (μ)	26.6°
Young's Modulus (E)	70 GPa
Unbalanced force ratio	0.0001

These parameters where chosen to represent realistic values that have been measured experimentally by other researchers. Simulations were undertaken on uniform PSDs containing a single fraction, which are shown in Table 2:

Table 2. PSD ranges and entropy coordinates.

ID	Range	A	B
A1	1-2	1	0
A2	0.5-1	0.75	0
A3	0.25-0.5	0.5	0
A4	0.125-0.25	0.25	0
A5	0.0625-0.125	0	0

4 RESULTS

Figure 1 shows the deviatoric stress (q) during the first 5% axial strain (ε_a):

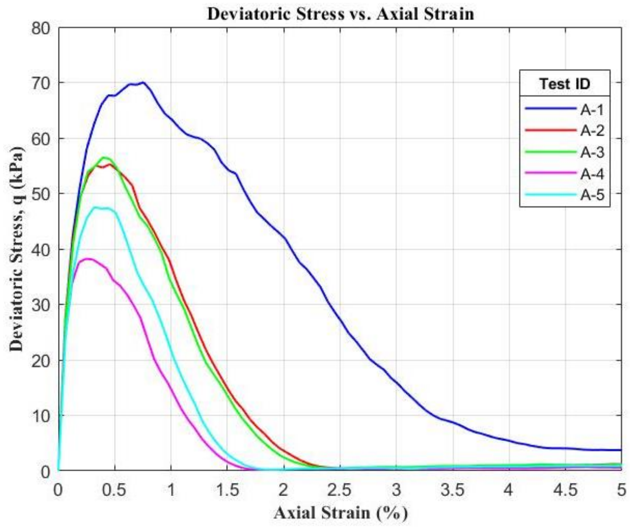

Figure 1. Deviatoric stress during the first 5% axial strain.

In all specimens but A-1, the deviatoric stress increases after the initiation of loading, but immediately reduce to near zero around 1.5% - 2.5% axial strain. Specimen A-1 shows the highest peak stress, followed by A-3, A-2, A-5 and A-4. Generally, as the A-coordinate increases, q_{peak} also increases, highlighting a relationship between stability and grain size. A-1, with the largest grain size, does not drop to a state *q=0*, indicating that it underwent more stable behaviours. Specimens A-2 and A-3 share similar stress relationships, with A-3 experiencing a slightly higher peak stress.

Figure 2 shows the initial mechanical coordination number (Zm_0) plotted with each specimen A-coordinate.

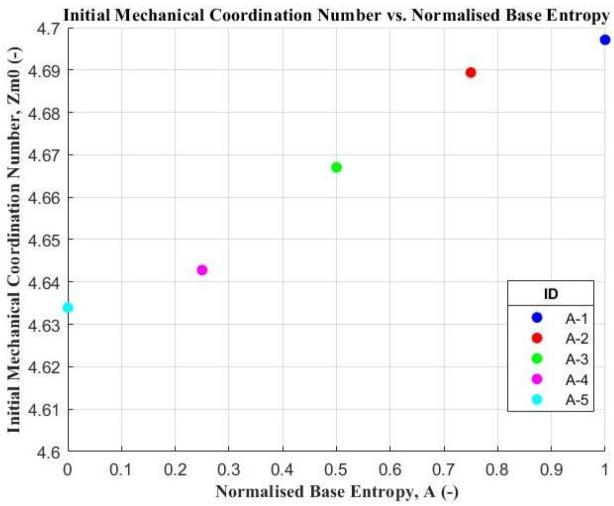

Figure 2. Initial mechanical coordination, Zm_0, number with normalised base entropy, A.

There is a relationship between the Zm_0 and decreasing A-coordinates. In other words, as the PSD decreases the specimens exhibit fewer stable tendencies. Note that these decreases in the Zm_0 align with the decreases in q_{peak} seen in Figure 1. It is suggested that as a result of changing the PSD, the ability for stress transmitting contacts to form is reduced; thus reducing the overall stability of the soil.

In Figure 3, to understand the contact behaviour at the initiation of liquefaction, *Zm* values corresponding to the minimum mean effective stress (*p'*) in each specimen are plotted against their A-coordinates, i.e. the initiation of liquefaction. The decrease in *Zm* at the onset of liquefaction follows the same relationship seen in Figure 2, with Zm_0, indicating that the PSD influences stability (by means of particle contacts) during the initiation of liquefaction and this may be an inherent property of different PSDs. Whilst further research is needed, the results presented here may indicate that the threshold coordination discussed by Wen and Zhang (2022), amongst others, may be PSD dependant, at least under monotonic conditions.

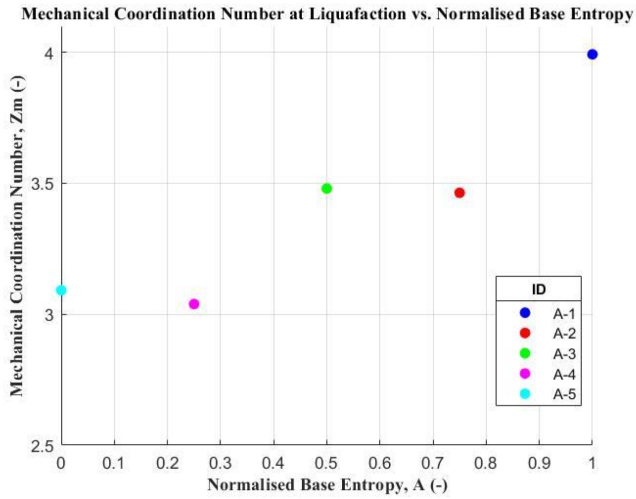

Figure 3. Mechanical coordination number, Zm at the initiation of liquefaction with normalised base entropy, A.

The figures thus far indicate that a correlation exists between the PSD and the stability of a soil during the initiation of liquefaction. This correlation may further be understood with reference to the deviatoric fabric component of the 2nd order fabric tensor (Φ_d), discussed by Satake (1982).

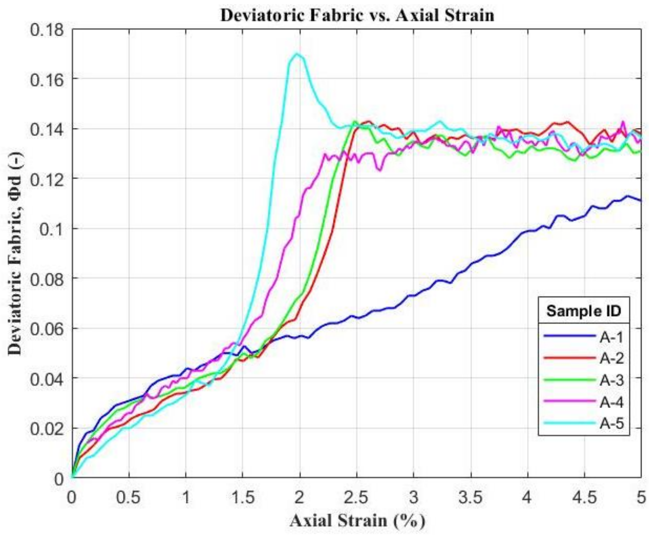

Figure 4. Deviatoric fabric during the first 5% axial strain.

Specimen A-1 shows a steady increase in Φ_d throughout the first 5% strain. Before q_{peak} at around 0.5% strain, A-1 has the largest Φ_d. In other words, it is the most anisotropic specimen at this point. It is important to note that changes in anisotropy in this work are not due to changes in stress path but are instead a result of changing PSD. A-1 is the most anisotropic specimen up to 1.5% strain. Following failure (2% - 2.5% strain), A-1 shows the lowest values of Φ_d, despite initially showing the largest values of Φ_d prior to failure. Despite this shift, A-1 presents a steadily growing fabric network as strain increases. Other specimens in Figure 4 show the opposite behaviour. They are generally more isotropic prior to failure but following the onset of liquefaction a notable shift in the fabric structure takes place and all specimens (except A-1) rapidly become significantly more anisotropic as their initial fabric was broken.

Figure 5 shows the q-ε_a relationship until a termination strain of 60%. The figure indicates that the initial fabric behaviours are evidently important throughout entirety of loading. Following failure, specimen A-1 exhibits large fluctuations in deviatoric stress indicating that within this specimen, new interparticle contacts were able to be created following failure. Specimen A-1 has been shown to be the most stable PSD throughout this work, which is also indicated by its drop to only around 5 kPa as opposed to near 0 kPa. The fluctuations in stress between 25% - 40% strain highlight the specimens inherent stability, which appears to be related to its ability to retain its grain structure. Whilst other specimens show some slight increases in stress post failure, it is evident that the change in the fabric structure at 2% - 2.5% strain has inhibited these specimens ability to regain interparticle contacts.

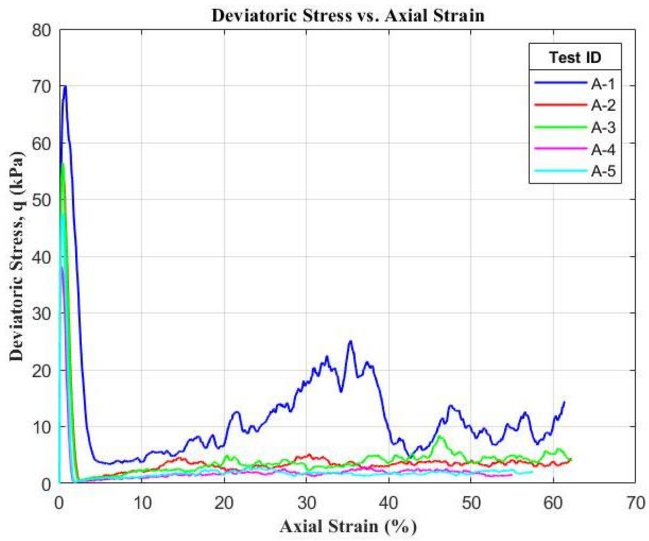

Figure 5. Deviatoric stress vs axial strain to simulation termination (55% - 60% strain).

5 DISCUSSION AND CONCUSIONS

This work has presented undrained monotonic DEM simulations of 5 PSDs. A relationship has been seen between grain size and stability/resistance to liquefaction. By examining the contact behaviours, it is suggested that larger average grain sizes can greatly increase a soils stability by enabling the soil fabric structure to resist breaking and thus rearrangement, likely as a result of creating strong fabric networks. It was seen in A-1, with the largest grain size, that this specimen steadily increased its contact network following failure. Whereas specimens with smaller grains had their contact network broken, which inhibited their ability to regain contacts following liquefaction.

This also appears to be related to the anisotropy of the grains. Breaking the fabric network made it so that soils which initially showed greater degrees of isotropy become significantly more anisotropic during liquefaction. Whereas A-1, which initially showed the greatest anisotropy, became the most isotropic specimen following failure and was the most stable specimen. These results indicate that anisotropy in soils, resulting from PSD alone, may render soils more susceptible to liquefaction.

REFERENCES

Barreto, D., Leak, J., Dimitriadi, V., McDougall, J. (2019). ‘Grading Entropy Coordinates and Criteria for Evaluation of Liquefaction Potential’, In *Earthquake Geotechnical Engineering and Protection and Development of Environment and Constructions*, (1346-1353).

J. Lőrincz, (1986). Grading entropy of soils. Doctoral thesis, Technical Univ. of Budapest, Hungary.

Manmatharajan, M. V, Edouardine-Pascale. I., Alex, S. Ghafghazi, M (2023). 'Effect of particle size and particle size distribution on the post-liquefaction strength of granular soils', *Soils and Foundations*, 63(4), p. 101336. Available at: https://doi.org/10.1016/j.sandf.2023.101336.

Otsubo, M. Chitrave, S. Kuwano, R. Hanley, K. H, Kyokawa. J Koseki (2022) 'Linking inherent anisotropy with liquefaction phenomena of granular materials by means of DEM analysis', *Soils and Foundations*, 62(5), p. 101202. Available at: https://doi.org/10.1016/j.sandf.2022.101202.

Satake, M. (1982). 'Fabric tensor in granular materials', In: Vermeer PA, Luger HJ (eds) IUTAM symposium on deformations and failure of granular materials. Balkema, Rotterdam, pp 63–68.

Tsuchida, H. & Hayasi, S. (1971). 'Estimation of liquefaction potential of sandy soils', In *Proceedings of the Third Joint Meeting*, US-Japan Panel on Wind and Seismic Effects, UJNR, Tokyo, May 1971, pp. 91-109.

Wang, R. *et al.* (2020), 'Post-liquefaction Cyclic Shear Strain: Phenomenon and Mechanism', in *Model Tests and Numerical Simulations of Liquefaction and Lateral Spreading*. Cham: Springer International Publishing, pp. 653–656. Available at: https://doi.org/10.1007/978-3-030-22818-7_38.

Wen, Y., Zhang, Y (2022). 'Relation between void ratio and contact fabric of granular soils'. *Acta Geotech.* **17**, 4297–4312 https://doi.org/10.1007/s11440-022-01507-7.