

Figure 1. Particle size distribution for the clean sand and mixtures and numerical samples prepared.

At the end of the isotropic compression stage, μ for sand particles is changed to 0.25 while for rubber particles μ remains unchanged. Samples are sheared under CU conditions. The strain rate ($\dot{\epsilon}$) is so that the inertial number (I) is kept to $I \leq 2.5e-3$, ensuring quasi-steady conditions during the shearing process (Midi 2004; da Cruz et al. 2005; Lopera Perez et al 2016). Table 1 summarizes the simulations carried out in this study, where samples are labelled indicating first the percentage of rubber content followed by p'_0 and the type of test. Unless otherwise indicated, results shown in this study correspond to tests sheared from a p'_0 of 200 kPa.

Table 1. List of simulations conducted.

Set test ID	p'_0 (kPa)	e_0	Rubber content (%)	Sand particles	Rubber particles
0R-50-CU	50	0.642	0	10,184	0
10R-50-CU	50	0.642	10	8,212	1,972

20R-50-CU	50	0.641	20	6,916	3,268
30R-50-CU	50	0.640	30	5,945	4,239
0R-100-CU	100	0.640	40	10,184	0
10R-100- CU	100	0.640	50	8,212	1,972
20R-100- CU	100	0.640	10	6,916	3,268
30R-100- CU	100	0.640	20	5,945	4,239
0R-200-CU	200	0.642	30	10,184	0
10R-200- CU	200	0.641	40	8,212	1,972
20R-200- CU	200	0.640	50	6,916	3,268
30R-200- CU	200	0.640	10	5,945	4,239

3. Results

3.1 Conventional undrained (CU) simulations

Macro-mechanical response

The deviatoric stress (q) is plotted against the major principal strain ϵ_1 in Figure 3. Zornberg et al. (2004) and Mashiri et al. (2015) noticed from experimental tests under drained conditions the increase in peak strength from tests with a rubber content that no greater than 30%. Opposite trend was found by Kawata et al (2008) from laboratory experiments under CU conditions. Results from Figure 3 indicate a decrease in peak strength as rubber content increases is dependent on loading conditions. Under the initial packing density the clean sand is seen to liquefy; samples with rubber content of 10% initially lose all strength to $q = 0$ kPa; however at larger strains (8% - 12% of ϵ_1) these samples find a suitable fabric structure that allows a regain strength (Sitharam et al., 2009). At rubber contents of 20% and 30%, samples do not liquefy and on the contrary experienced a QSS that is attained at larger deviatoric stress as rubber content increased. Interestingly, samples that liquefy show a higher initial peak in deviatoric stress while samples that tend to dilate (increase in q soon after QSS) found lower initial peaks in q .

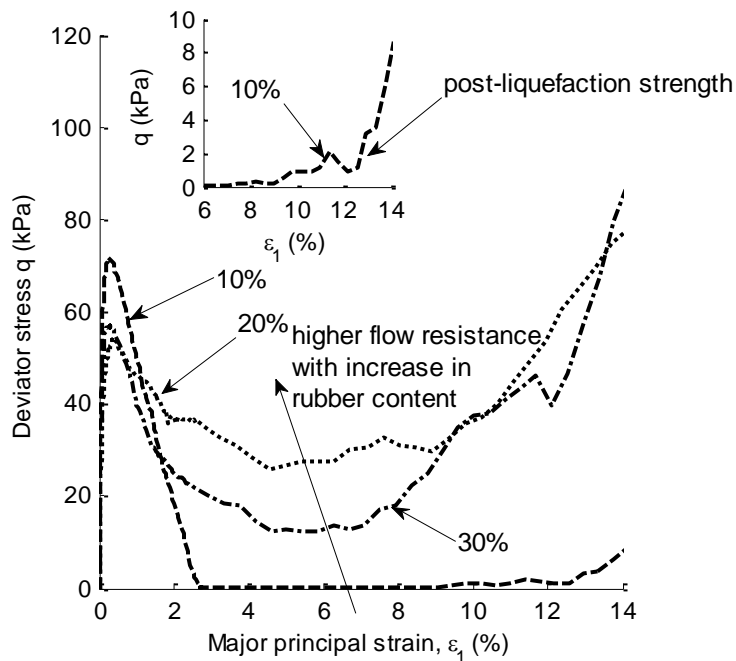


Figure 2. Deviatoric stress against major principal strain.

Micro-mechanical response

Relative contribution to the deviatoric stress

From the contacts cumulative contribution to the deviatoric stress (Radjai et al., 1998) it is possible to explore how each type of contact is contributing to the deviatoric stress. Contact types are divided in this study as: sand-sand (s-s), rubber-sand (r-s) and rubber-rubber (r-r) contacts.

Figure 3 illustrates the relative contribution to the deviatoric stress by each type of contact. The contribution to the peak strength is shown in Figure 3a, where it is noticed how as the number of rubber particles increases the less contribution to q is carried out by s-s contacts. Nevertheless, at peak strength, s-s contacts contribute to the total deviatoric stress in the range of 60% to nearly 90, depending on the rubber content. r-s contacts at most are seen to exceed 30% of relative contribution to q at a rubber content of 30%, while the contribution from r-r contacts does not reach 1% even for the sample with rubber content of 30%. Figure 3b presents the contribution to the deviatoric stress at quasi-steady state. Only the relative contribution to q from rubber contents of 10% and 20% are included as for the clean sand and at rubber contents of 10% q drops to zero. At QSS, the relative contributions to q for the sample with 20% of rubber content slightly changes for s-s and r-s contacts and only a noticeable change is seen for r-r contacts. More obvious changes are seen for rubber content of 30% where the s-s contribution drops below 60%, while r-s contacts almost reach 40% and r-r contacts contribute more than 4% to the

overall q . Figure 5 reveals how contacts that involve rubber particles become more important at QSS than at q_{peak} , where the high frictional attribute from rubber particles is taken in advantage helping to provide resistance against further dropping in strength and thus avoiding liquefaction.

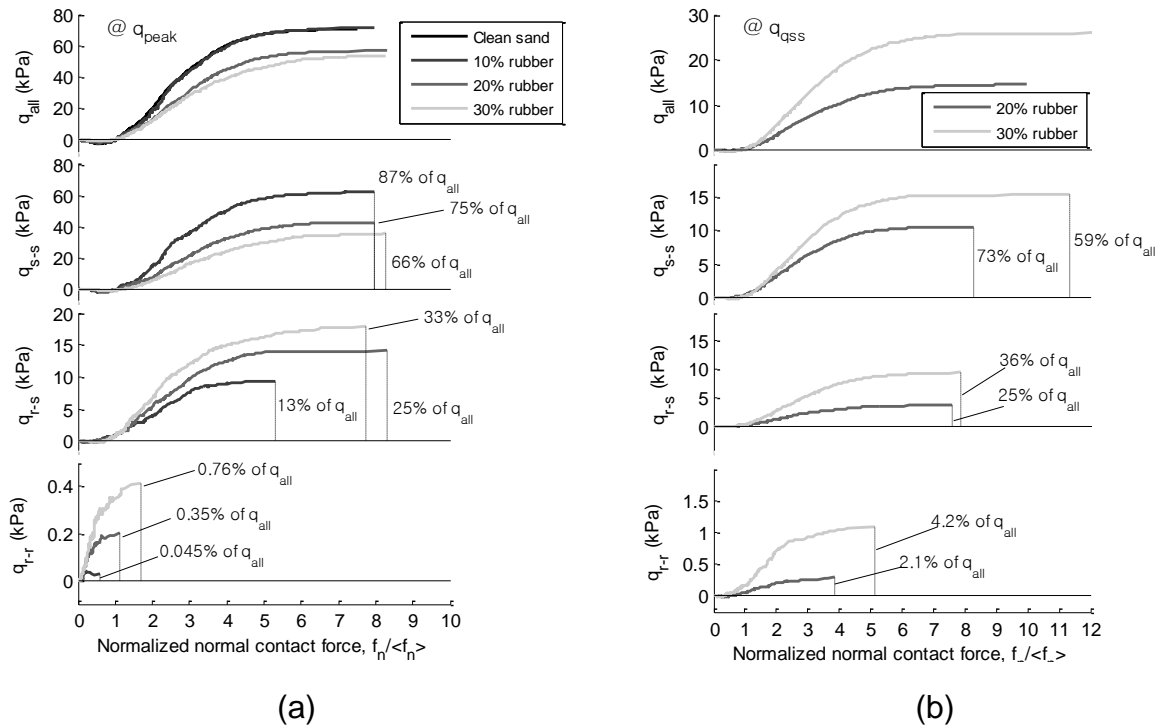


Figure 3. Cumulative contribution to q at (a) peak of q and (b) at quasi-steady state.

Contact force networks

A view of the contact force network for a rubber content of 30% at peak strength and at quasi-steady state is shown in Figure 4. At peak strength it is clear how the main contribution to the strength of the system is given by sand-sand contacts that present stronger contacts vertically aligned. Although strong contacts are also visible in the rubber-sand network, these contacts are seen more randomly oriented contributing in less proportion to the stress transmission within the system. Rubber-rubber contacts are present as floating contacts unable to form load bearing columns and thus the stress transmission is not possible through these contacts. At quasi-steady state, although stronger contacts are still present in the sand-sand contact network, it is obvious a decrease in strong contacts in the sand-sand network while an increase in the rubber-sand network. Additionally, the stronger rubber-sand contacts are seen more oriented vertically than horizontally explaining the increase in contribution to deviatoric loading from these

contacts. Rubber-rubber contacts are seen to become closer together at quasi-steady state where load bearing columns are distinguished. The high-frictional rubber particles help to prevent particles to slide which leads to the formation of a stable contact network that is capable to withstand the imposed deviatoric loading and further deviatoric increments.

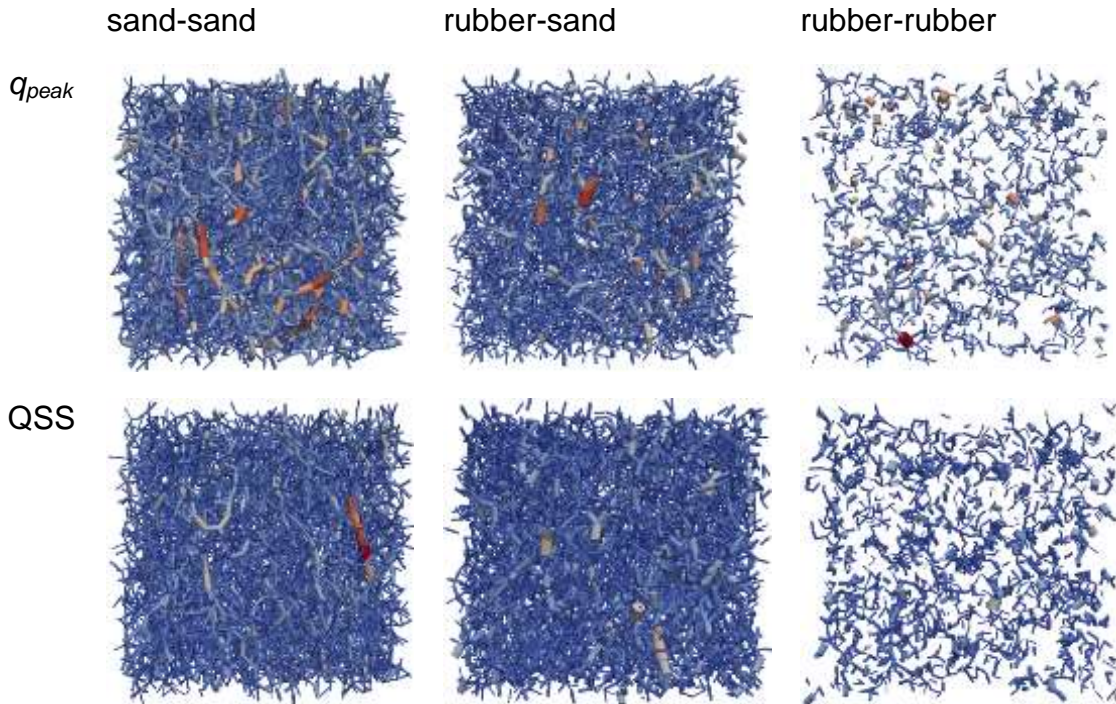


Figure 4. Contact force network for each mixture by type of contact at quasi-steady state. Thicker cylinders indicate larger normal contact force.

Conclusions

A series of DEM simulations of sand-rubber mixtures tested under conventional undrained and constant shear drained conditions have been carried out. Rubber contents ranged from 0% to 30% by mixture weight. The macro-mechanical response and the intrinsic micro-mechanisms experienced by the clean sand and mixtures were explored and the following conclusions can be drawn:

- Loose samples sheared under CU conditions reach lower peak strengths as rubber content increases. However, higher peak strength is not an indication of higher resistance against liquefaction. Instead, as rubber content increased total liquefaction is inhibited with the samples with 10% of rubber content showing post-liquefaction resistance while those with 30% of rubber content avoiding liquefaction and only experiencing a limited decrease in deviatoric stress.
- From the particle-scale analysis it is revealed that very different patterns appear at peak strength and at QSS as rubber content increases. Samples with low rubber content ($< 20\%$) become unstable preventing the formation of a contact network capable to withstand the deviatoric loading. The opposite is found for higher rubber contents ($\geq 20\%$) where with help of rubber particles is sufficient to achieve higher contact network and force anisotropy that allows the system to come upon a QSS avoiding liquefaction.

Acknowledgments

This study was supported by The University of Hong Kong SPACE research fund. This research was conducted using the HKU Information Technology Services research computing facilities that are supported in part by the Hong Kong UGC Special Equipment Grant (SEG HKU09). The third author would like to acknowledge a grant from the Faculty of Engineering UNSW (FRG) for supporting his trips to Hong Kong for collaboration.

References

- Anastasiadis A. Senetakis K. and Ptilakis K. (2012). Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures. *Geotechnical and Geological Engineering*, 30 (2), 363 – 382.
- Castro G. (1969). Liquefaction of sands. PhD Thesis, Harvard Soil Mechanics Series, No. 81, Harvard University, Cambridge, MA.
- Cundall P. A. and Strack O. D. L. (1979). A discrete element model for granular assemblies. *Géotechnique*, 29, No. 1, 47 – 65.
- da Cruz F., Emam S., Prochnow M., J. N. Roux and F. Chevoir (2005). Rheophysics of dense granular materials: Discrete simulation of plane shear flows. *Physical Review E*, 72, 021309.
- Evans T. M. and Valdes J. R. (2011). The microstructure of particulate mixtures in one-dimensional compression: numerical studies. *Granular Matter*, 13 No. 5, 657 – 669.

- Fuchiyama, M. and Konja, A., (2016). Compression and shear behavior of tire chips and prevention effect of liquefaction. *Japanese Geotechnical Society Special Publication*, 2 (61), pp.2086-2089.
- Hong Y., Yang Z., Orense R. P. and Lu Y. (2015). Investigation of sand-tire mixtures as liquefaction remedial measure. *Proceedings of the tenth pacific conference on earthquake engineering Building an Earthquake-resilient pacific*, November 6–8, Sydney, Australia.
- Hyodo, M., Yamada, S., Orense, R., Okamoto, M. and Hazarika, H. (2007). November. Undrained cyclic shear properties of tire chip-sand mixtures. In *Proceedings of the international workshop on scrap tire derived geomaterials—opportunities and challenges*, Yokosuka, Japan, 187-196.
- Ishihara, K. (1993). Liquefaction and flow failure during earthquakes. *Geotechnique*, 43 (3), 351-451.
- Kawata, S., Hyodo, M., Orense, P., Yamada, S. and Hazarika, H. (2007). November. Undrained and drained shear behavior of sand and tire chips composite material. In *Proceedings of the international workshop on scrap tire derived geomaterials—opportunities and challenges*, Yokosuka, Japan, 277-283.
- Lade P.V. (1992). Static instability and liquefaction of loose fine sandy slopes, *Journal of Geotechnical Engineering*, 118(1):51-71
- Lee C., Shin H. and Lee J. (2014). Behaviour of sand-rubber particle mixture: experimental observations and numerical simulations. *International Journal for Numerical and Analytical Methods in Geomechanics*, 38, 1651 – 1663.
- Lopera P, J. C, Kwok, C.Y., Huang, X. and Hanley, K.J. (2016). Assessing the quasi-static conditions for shearing in granular media within the critical state soil mechanics framework. *Soils and Foundations*, 56(1), 152-159.
- MiDi G. D. R. (2004). On dense granular flows. *European Physical Journal*, E 14, 341 – 365.
- Murthy, T.G., Loukidis, D., Carraro, J.A.H., Prezzi, M. and Salgado, R. (2007). Undrained monotonic response of clean and silty sands. *Géotechnique*, 57(3), 273-288.
- Olson S. M., Stark T. D., Walton W. H., and Castro, G. (2000). 1907 static liquefaction flow failure of the north dike of Wachusett dam. *J. Geotech. Geoenviron. Eng.* 126(12), 1184–1193.
- Radjai F., Wolf D. E., Jean M., and Moreau J. (1998). Bimodal character of stress transmission in granular packings. *Physical Review Letters*, 80 No. 1, 61 – 64.
- Schallamach A. (1958). Friction and abrasion of rubber. *Wear*, 1(5) 384 – 417.

Sitharam, T.G., Vinod, J.S. and Ravishankar, B.V. (2009). Post-liquefaction undrained monotonic behaviour of sands: experiments and DEM simulations. *Géotechnique*, 59(9), 739-749.

Sladen, J. A., D'Hollander, R. D., and Krahn, J. (1985). The liquefaction of sands, a collapse surface approach. *Can. Geotech. J.* 22(4), 564–578.

Uchumira T., Chi N., Nirmalan S., Sato T., Meidani M. and Towhata I. (2007). Shaking table tests on effect of tire chips and sand mixture in increasing liquefaction resistance and mitigating uplift of pipe. In: Hazarika and Yasuhara (eds) *Proceedings, international workshop on scrap tire derived geomaterials—opportunities and challenges*, Yokosuka, Japan, 179–186.

Valdes J. R. and Evans M. T. (2008). Sand-rubber mixtures: experiments and numerical simulations. *Canadian Geotechnical Journal*, 45 No. 4 588 – 595.

Zornberg J. G., Carbal A. R. and Viratjandr C. (2004). Behaviour of tire shred–sand mixtures. *Canadian Geotechnical Journal*, 41:227–241.