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Influence of rubber content on static liquefaction of sand-rubber mixtures

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Abstract

While it has been acknowledge from cyclic laboratory tests that the inclusion of rubber particles increases liquefaction resistance, little attention has been paid to the influence of rubber content on static liquefaction. Laboratory experiments of sand-rubber mixtures under undrained loading have offered macro-scale insight into their stress-strain response, leaving the micro-mechanics under such conditions yet to be explored. This study presents a series of undrained monotonic triaxial tests consisting of mixtures of sand (stiff) and rubber (soft) particles simulated by the discrete element method (DEM). Sets of loose mixtures were prepared with rubber contents ranging from 0% to 30% by weight, having the same void ratio. The initial peak strength was encountered at lower strengths as rubber content increases; however, the angle of the instability line was seen independent of rubber content. As rubber content increased, less susceptibility to liquefaction was found with the sample having 30% of rubber content only experiencing limited flow. Micro-scale information, including coordination number, geometrical and mechanical anisotropy, was obtained for all the tests. Results from this contribution offer a micro-mechanical perspective of the undrained behaviour of sand-rubber mixtures, highlighting the importance of practicing engineers to understand new geomaterials, specifically sand-rubber mixtures where depending on the loading conditions together with rubber content, both positive (resistance to liquefy) or negative effects (lower peak strength) can be expected.

Keywords: Discrete-Element Modelling; Fabric/Structure of soils; Particle-Scale Behaviour; Sand-Rubber Mixtures; Liquefaction Susceptibility; Soil Instability[1]

1. Introduction

Several studies have focused on understanding the effect of rubber content on the liquefaction resistant of sand-rubber mixtures by conducting laboratory tests mostly by means of cyclic triaxial testing (Uchimura et al, 2007; Hyodo et al, 2008; Hong et al., 2015; Fuchiyama and Konja, 2016). While the liquefaction resistance and the corresponding volumetric threshold strain of sand-rubber mixtures have been widely studied under cyclic-dynamic test conditions, little attention has been given to the effect of rubber content on liquefaction under static loading. Static liquefaction is related with the instability of earth materials and many structures, which would be otherwise stable under given patterns of stress-state and loading conditions, may behave highly unstable under undrained monotonic loading if their state falls with a particular zone of behaviour close to the instability line (Lade, 1992). Thus, the behaviour of earth materials against static liquefaction is an important step in soil modelling and the prediction of their potential unstable behaviour.

The occurrence of unstable behaviour in granular materials under static loading has motivated a large number of studies on this topic (Castro, 1969; Sladen et al, 1985; Ishihara, 1993; Olson et al., 2000; Murthy, 2007). Under static loading, the addition of rubber content has been demonstrated to be beneficial against static liquefaction. Kawata et al, (2008) reported from triaxial tests on loose specimens of sand-rubber mixtures sheared under monotonic undrained loading limited flow (reduction in deviatoric stress) for loose sand while no flow for the same mixed with rubber particles. However, additional thorough work remains to be done to understand the micro-structural reasons behind the effect of rubber particles on the undrained monotonic behaviour of sand-rubber mixtures which is a widely unexplored area of research.

In order to address this issue, the discrete element method (DEM) (Cundall and Strack, 1979) offers a powerful tool to gain better insight into the instability and undrained behaviour of granular materials as it allows the tracking of particle contacts and the distribution and magnitude of forces at all test stages that are not feasible in laboratory experiments. In this study, mixtures of rubber and sand particles are simulated in three dimensional triaxial monotonic compression tests employing the discrete element method. Sand particles are modelled as rigid particles with a high stiffness, whereas rubber

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particles are modelled as soft particles having a low stiffness. The purpose of this contribution is to explore the micro-mechanics developed on loose specimens or sand-rubber mixtures sheared under conventional undrained (CU) conditions. Special attention is given to the onset of instability (initial peak in deviatoric stress) and at liquefaction or quasi-steady state. The contribution that each type of contact, i.e. sand-sand, rubber-sand or rubber-rubber, makes to both the micro- and macro-mechanical responses is also investigated.

2. Numerical simulations

The particle size distribution (PSD) of the simulated sand matches that of a uniform sand that closely matches the fluvial sand studied by Anastasiadis et al (2012) as indicated in Figure 1. Rubber particles follow the same PSD of the simulated sand. Mixtures considering are prepared at 0%, 10%, 20% and 30% of rubber content by mixture weight. A simplified Hertz-Mindlin contact model is used in the simulations. Sand particles are given a Poisson's ratio of 0.12 and a a shear modulus (G_s^p) of 10 GPa. Rubber particles are simulated as soft particles with a Poisson's ratio of 0.45 consistent with the small volume compressibility of rubber (Beatty (1991) and a shear modulus (G_r^p) of 12 MPa. A local damping coefficient of 0.1 is used for all simulations where gravity is inactive. Each sample has a number of 10,184 particles. During the isotropic compression stage, the periodic cell is deformed until the mean effective stresses reaches 50 kPa, 100 kPa and 200 kPa, indicating the initial mean effective stress (p'_0). During isotropic compression stage, the inter-particle friction coefficient (μ) varied for sand particles in the range of 0.15 to 0.16 in order to yield a similar loose void ratio (e_0) of 0.640 for all three mean effective stresses. μ for rubber particles corresponds to 1.0 in line with previous experimental and numerical works (Schallamach, 1958; Valdes & Evans 2008; Evans & Valdes 2011; Lee et al. 2014). Views of the prepared samples at p'_0 = 100 kPa are included in Figure 1.

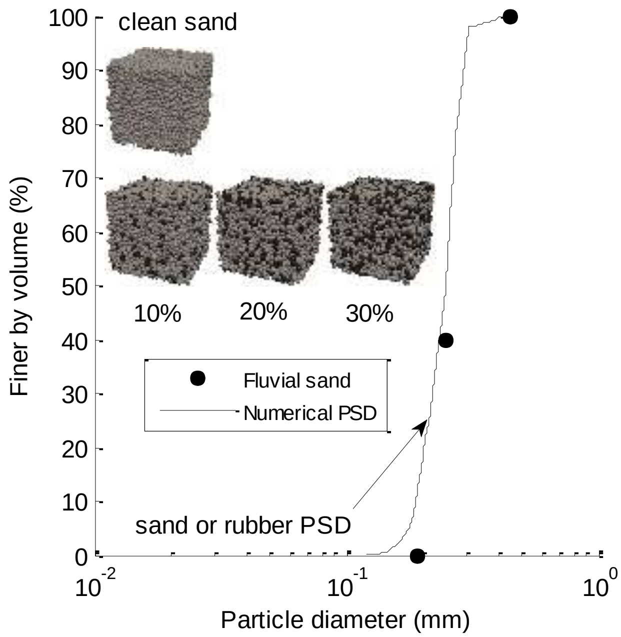


Figure 1. Particle size distribution for the clean sand and mixtures and numerical samples prepared.

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 ($\dot{\varepsilon}$) is so that the inertial number (I) is kept to $I \leq 2.5e\text{-}3$, 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.

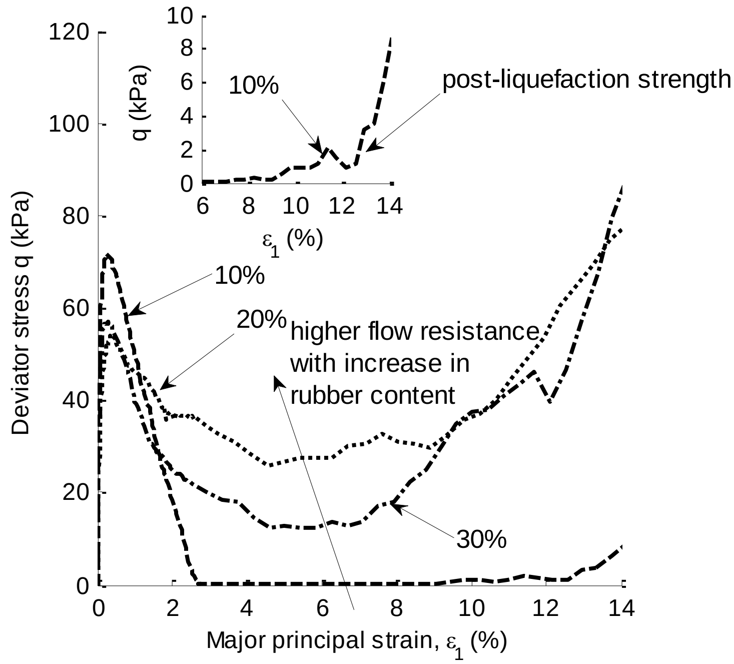


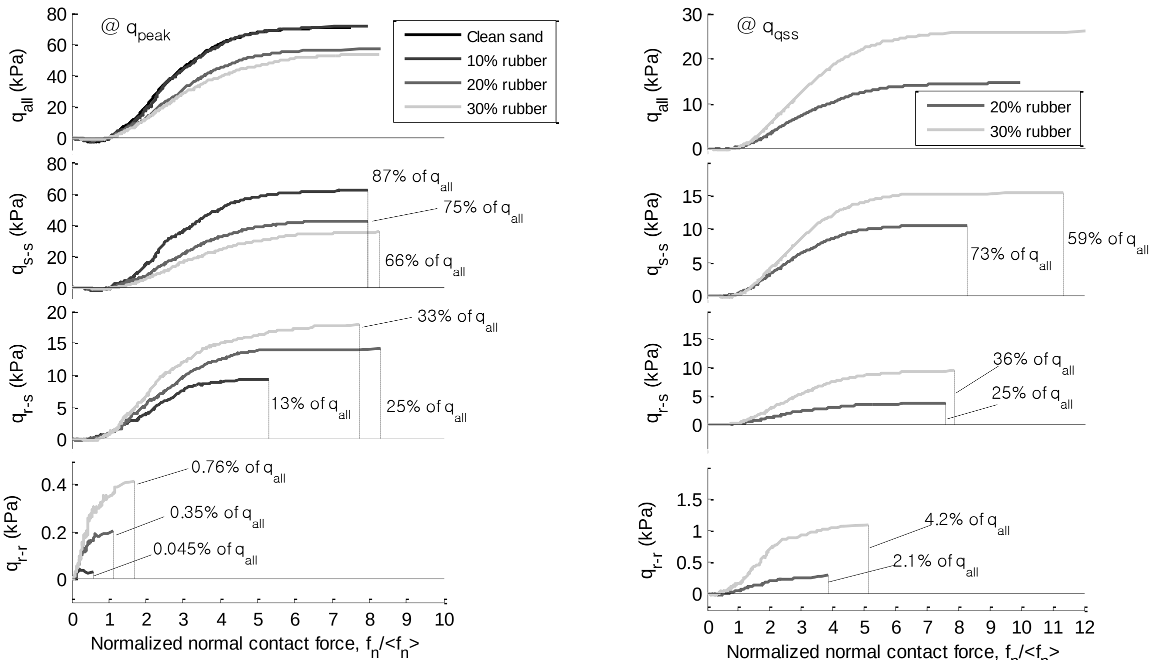
Figure 2. Deviatoric stress against major principal strain.

<u>Micro-mechanical response</u>

<u>*Relative contribution to the deviatoric stress*</u>

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.



(a) (b)

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.

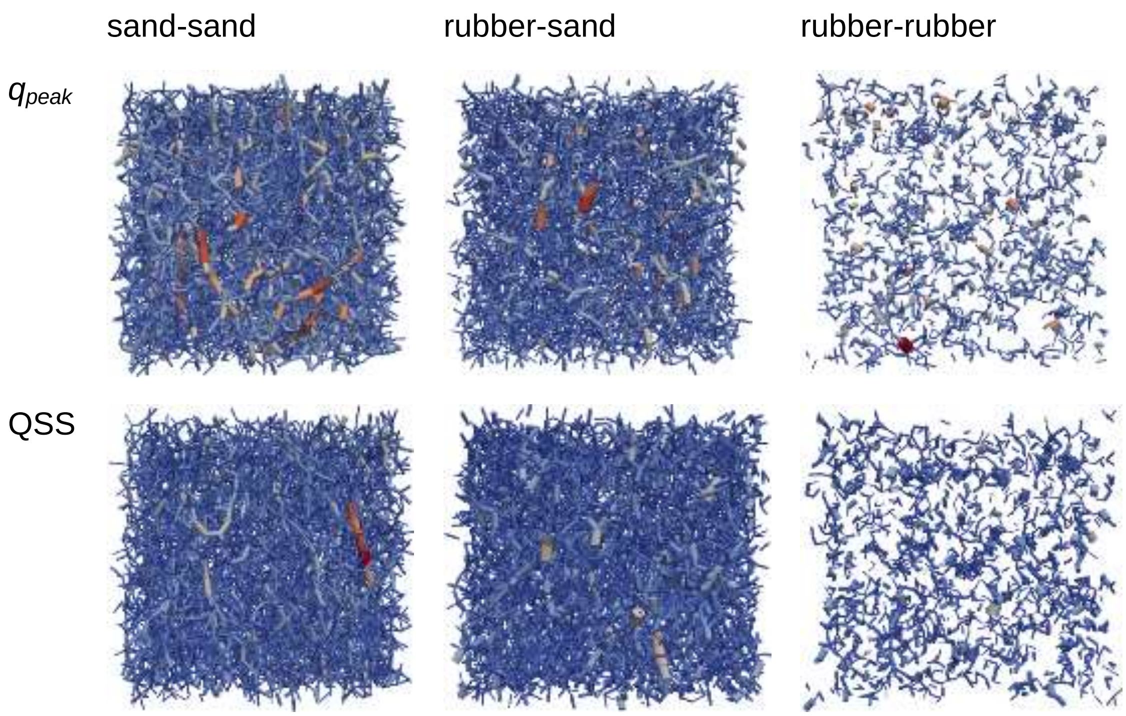


Figure 4. Contact force network for each mixture by type of contact at quasi-steady state. Thicker cylinders indicate larger normal contact force.

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 (≥ 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.

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