



Effects of cementation on the cyclic resistance of granular soils with presence of initial static shear stress

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Abstract

In engineering applications such as non-invasive cementation beneath existing structures or naturally induced cementation around piles, cementation can develop in soils that have previously undergone initial static shear. However, the joint effect of cementation and initial static shear stress on subsequent cyclic loading behaviour remains largely uninvestigated, despite its crucial importance for understanding foundation response to seismic events and cyclic loading conditions. This study investigates the combined effects of cementation and initial static shear stress on the subsequent cyclic behaviour of granular soils using the discrete element method (DEM). First, DEM specimens with varying levels of cementation are subjected to undrained cyclic loading under different cyclic stress ratios (CSR) without initial static shear stress and the results align well with experimental results reported in the literature. Then, the role of initial static shear stress on the undrained cyclic response of the specimens is investigated. The results indicate that the liquefaction resistance of cemented soil depends on both CSR and initial static shear stress. The effect of initial static shear stress, which can be either beneficial or detrimental, is more pronounced at low CSR values. A new empirical equation is proposed to describe the relationship between the number of cycles to liquefaction with CSR, cementation level and initial static shear stress, providing the first predictive framework for their coupled effects on liquefaction resistance. Micromechanical analysis reveals that cementation helps maintain structural stability by preventing contact loss between particles, while initial static shear stress accelerates contact degradation and reduces structural stability during cyclic loading. These insights contribute to the development of multiscale constitutive models for cemented soils under cyclic loading conditions.

Keywords Cemented granular soil · Cyclic loading · DEM · Initial shear

1 Introduction

Soils subjected to cyclic loads are commonly encountered in scenarios ranging from seismic events (e.g. earthquakes) and traffic-induced vibrations on road embankments to the operational conditions of offshore wind turbine pile foundations. The response of soil under such cyclic loading conditions is characterised by complex mechanisms involving progressive accumulation of plastic strains, changes in soil fabric, and potential development of excess pore water pressures [22, 37, 47]. It is possible to trigger soil liquefaction under cyclic loading and hence pose damage to surrounding infrastructures. A fundamental understanding of the cyclic behaviour and liquefaction resistance of soils is important for developing soil-predicting models, mitigating failure risks for structures such

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as offshore wind turbines (OWTs) [21, 23], and promoting the installation of OWTs by vibratory driving.

Extensive studies have been conducted to build a fundamental understanding of the soil behaviour subjected to cyclic loading. These works primarily involve the investigation of isotropically consolidated specimens under symmetrical loading in compression and extension [33, 41]. Although this loading condition represents practical scenarios such as the free-field level ground under earthquakes [48], it is not applicable to conditions such as soils beneath a structure (Fig. 1) or in a sloping ground [47, 50], where soils may have undergone initial static shear before the cyclic loading. In this context, the cyclic behaviour of soils with the presence of initial static shear stress has been evaluated [27, 35, 40, 47, 48, 50]. These results highlight the important role of the initial static shear stress, in addition to the initial packing density and effective confining pressure, on the cyclic behaviour and liquefaction resistance of soils. For instance, Harder and Boulanger [11] reported that the effect of initial static shear stress is beneficial to liquefaction resistance for dense sand but is detrimental to loose sand. Yang and Sze [47] found that it is beneficial to the liquefaction resistance of loose

sand at low levels of initial static shear stress, while it becomes detrimental at high levels.

In addition to experimental tests, numerical approaches, particularly the discrete element method (DEM), have been adopted to evaluate the complex soil response under a wide range of conditions, offering insights that are not accessible from experimental observations [8, 14, 16, 43]. For instance, DEM was used to investigate the cyclic responses of sands with different properties, such as inherently anisotropic sands [44], specimens with different fabric anisotropy [55], consolidation state [49] and initial static shear stress [58]. In addition, the effects of various test conditions, including the confining pressure [38] and cyclic and static stress ratios [17], were also reported, indicating that DEM is a powerful tool for investigating the cyclic behaviour of granular soils. Moreover, DEM is particularly advantageous for investigating cemented granular materials, as it enables precise control of cementation distribution (e.g. homogeneous bonding) and direct tracking of bond breakage evolution [34, 57], both of which are challenging to achieve in experiments.

To mitigate the potential soil liquefaction due to seismic events, soils need to be reinforced through a process usually referred to as ground improvement. Among various ground improvement methods, non-invasive methods, which have minimal disturbance to the surrounding environment, are preferable for treating soils beneath structures. A typical non-invasive method is microbially induced carbonate precipitation (MICP) [26, 46, 56], it involves injecting a cementation solution (containing calcium chloride and urea) along with a bacterial solution, utilising natural bio-mineralisation processes to drive carbonate precipitation, thereby cementing the soil without altering the in-situ stress state. In this application, soil beneath structures (e.g. building foundations) often experiences static shear stress from structural loads prior to MICP treatment. Consequently, cementation is introduced into soil that has already undergone initial static shear. When subsequent seismic events occur, the cyclic response of this initial-sheared cemented soil becomes critical for foundation performance. In addition to artificially introduced cementation, as shown in Fig. 1, initial static shear stress can be applied on the soil around the pile shaft during pile installation [10]. During the operational time, natural cementation (e.g. calcite) can precipitate around the pile foundation [2, 5], an effect called soil ageing. Meanwhile, the soil surrounding the pile is subjected to cyclic loading from the dynamic forces of OWT, which interact with both the initial static shear stress and cementation. Consequently, the initial static shear stress and the precipitated natural cementation have a joint impact on the operational performance of OWTs. Moreover, at the end of an OWT's lifetime, the vibro-extraction method can be employed for

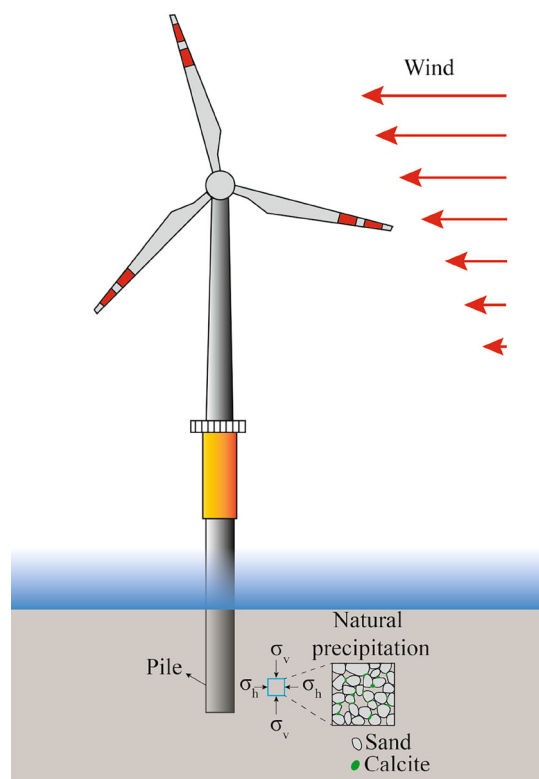


Fig. 1 Schematic illustration demonstrating that cementation is introduced into the soil element that has already undergone initial static shear: natural cementation precipitated in the soil around the OWT foundation

pile removal, where inducing soil liquefaction can facilitate pile extraction [28]. Therefore, understanding the cyclic behaviour of cemented soil with the presence of initial static shear stress is important for optimising ground improvement strategies, ensuring the long-term serviceability of OWTs and promoting their extraction through vibro-extraction at the end of the pile lifetime.

Despite the crucial importance of understanding the cyclic response of cemented soils with the presence of initial static shear stress, knowledge gaps exist in this area: current research primarily focuses on the individual effects of either cementation or initial static shear stress on the cyclic behaviour of soil. For instance, Zhang et al. [57] employed DEM to investigate the cyclic liquefaction behaviour of cemented sand, with all the specimens being in an isotropic stress state prior to cyclic loading. Pan and Yang [27] and Wei and Yang [40] conducted experiments to examine the effect of initial static shear on the cyclic resistance of sands. However, the joint effect of cementation and initial static shear stress has not been comprehensively investigated through experimental studies or numerical simulations. Specifically, it remains unclear how much cementation should be introduced to achieve desirable liquefaction resistance under varying initial static shear conditions for liquefaction mitigation purposes, or conversely, how much effort should be applied to trigger liquefaction to facilitate the extraction of aged piles. Furthermore, during cyclic loading, it is challenging in experiments to access and monitor the evolution of microstructural properties that govern the macroscopic response of cemented soils. These knowledge gaps limit our ability to optimise ground improvement strategies and predict the long-term performance of foundations subjected to both cementation and initial shear stress. Therefore, this study aims to:

- Develop a comprehensive DEM framework to investigate the combined effects of cementation, initial static shear stress (SSR), and cyclic loading on granular soil behaviour.
- Quantify and establish the relationship between liquefaction resistance and cementation levels under different initial static shear conditions.
- Quantify microstructure evolution during cyclic loading to provide insights into the underlying mechanisms governing the macroscopic response.

This study is organised as follows: details of DEM simulations are given in Sect. 2. The simulation results in terms of the macroscopic cyclic response and microscopic insights are presented and discussed in Sects. 3 and 4, respectively. Section 5 summarises the main conclusions of this study.

2 DEM simulations

In this section, the adopted inter-particle contact law is introduced, followed by the procedure of generating DEM specimens and the introduction of the undrained cyclic loading scheme.

2.1 Contact model

The DEM platform used in this study is YADE [36]. A cohesive-frictional contact model accounting for rolling and twisting resistance is used. Details of this contact model can be found in YADE documentation [36] and Zhang and Dieudonné [53]. For the sake of clarity, the contact law is also introduced below.

The normal force $\vec{F}_n$, incremental shear force $\Delta\vec{F}_s$, incremental rolling moment $\Delta\vec{M}_r$ and incremental twisting moment $\Delta\vec{M}_{tw}$ are calculated as:

$$\vec{F}_n = k_n u_n \vec{n} \quad (1)$$

$$\Delta\vec{F}_s = -k_s \Delta\vec{u}_s \quad (2)$$

$$\Delta\vec{M}_r = -k_r \Delta\vec{\theta}_r \quad (3)$$

$$\Delta\vec{M}_{tw} = -k_{tw} \Delta\vec{\theta}_{tw} \quad (4)$$

where u_n is the relative normal displacement of the two spheres, $\vec{n}$ is the normal contact vector, $\Delta\vec{u}_s$ is the incremental tangential displacement, and $\Delta\vec{\theta}_r$ and $\Delta\vec{\theta}_{tw}$ are the relative rotations due to rolling and twisting, respectively. k_n , k_s , k_r and k_{tw} are the contact normal stiffness, tangential stiffness, rolling stiffness and twisting stiffness, respectively, which are given by:

$$k_n = \frac{2E_1 R_1 E_2 R_2}{E_1 R_1 + E_2 R_2} \quad (5)$$

$$k_s = \nu k_n \quad (6)$$

$$k_r = \alpha_r R_1 R_2 k_s \quad (7)$$

$$k_{tw} = \alpha_{tw} R_1 R_2 k_s \quad (8)$$

where R_1 and R_2 , E_1 and E_2 are the radii, moduli of elasticity of the spheres, ν is the shearing stiffness coefficient, and α_r and α_{tw} are the rolling and twisting stiffness coefficients, respectively.

The normal, shear, rolling and twisting resistances are determined by:

$$F_n^{max} = \sigma_{coh} \cdot \min(R_1^2, R_2^2) \quad (9)$$

$$F_s^{max} = \|\vec{F}_n\| \tan \phi'_c + \sigma_{S-C} \cdot S_c = \|\vec{F}_n\| \tan \phi'_c + \sigma_{coh} \cdot \min(R_1^2, R_2^2) \quad (10)$$

$$M_r^{max} = ||\vec{F}_n||\eta_r \cdot \min(R_1, R_2) \quad (11)$$

$$M_{tw}^{max} = ||\vec{F}_n||\eta_{tw} \cdot \min(R_1, R_2) \quad (12)$$

where φ'_c is the contact friction angle and η_r and η_{tw} are the resistance coefficients of rolling and twisting, respectively. σ_{coh} is the inter-particle cohesive strength directly defined in the adopted DEM code. The validation of σ_{coh} and its corresponding CaCO_3 content is presented in Sect. 3.2. The DEM parameters are listed in Table 1.

2.2 Sample preparation and model parameters

The preparation of DEM specimens with different levels of initial static shear stress is illustrated in Fig. 2a, which consists of the following two steps.

i.

Isotropic compression. In this step, a sand packing containing 7000 spherical particles is generated. All the particles are randomly located inside a 7 cm × 7 cm × 14 cm box formed by six frictionless rigid walls. There is no contact between the particles at this stage. The radius expansion method is used for isotropic compression, during which the radii of the sand particles are increased proportionally to their initial size until the packing reaches a confining pressure of 50 kPa. The radius expansion is then turned off to fix the size of the particles (shown in Fig. 3). The inter-particle friction angle is progressively decreased by 5% every 500 numerical steps until the target porosity of 0.44 is reached. This iterative friction reduction method allows the packing to gradually densify and converge to the desired porosity. During this process, the rigid walls are controlled by a servomechanism to maintain the confining pressure. Once the target porosity is reached, the friction angle is set to the value used for the drained triaxial compression stage. After that, the isotropic

compression is continued by moving the walls (instead of through radii expansion) until the mean effective stress (p'), or equivalently the lateral confining pressure (σ'_h), reaches the target value. The set of target values (σ'_{h0}), ranging from 85 kPa to 100 kPa, is listed in Table 2. The width of the sample (7 cm) is 14 times the mean grain diameter (D_{50}), satisfying the size of a representative volume element (RVE) suggested by Gu et al. [7] and Schmidt et al. [32]. All sand grains are modelled using spherical particles. Particle shape has been found to affect the mechanical behaviour of soils [6, 24]. The effects of irregular particle shape are accounted for by incorporating rolling and twisting resistance in the contact law in this study, which has been widely adopted in DEM simulations for computational efficiency. Future studies using realistic particle shapes are recommended to better capture actual soil behaviour [12].

ii.

Drained triaxial compression. The consolidated specimens are subjected to drained triaxial compression. In this process, the lateral confining pressure remains constant at σ'_{h0} , while the vertical stress (σ'_v) increases. The loading is terminated when p' reaches 100 kPa (see Fig. 2a). From the above steps, the sand specimens subjected to different degrees of initial static shear are obtained. The degree of initial static shear can be described by the static stress ratio (SSR), which is the ratio of the static deviatoric stress (q_s) at the end of the drained triaxial compression to the mean effective stress (p'_0) as indicated in Fig. 2, $SSR = \frac{q_s}{2p'_0}$, with $q_s = \sigma'_{v0} - \sigma'_{h0}$, where σ'_{v0} is the effective stress along the vertical direction (loading direction) at the end of the drained triaxial compression. The information of initial static shear stress on each sample is summarised in Table 2. After that, the cementation is introduced at all grain contacts for building homogeneous cemented specimens by activating the contact cohesion (see Sect. 2.1). It should be noted that cementation in the soil matrix can exhibit several distribution patterns in real cemented soils, such as at contact points, filling particle gaps, or on particle surfaces [3, 20, 42, 54]. In this study, it is assumed that the cementation is distributed at contact points of sand grains, which is a widely used approach for simulating cemented soils using DEM [15, 19, 34].

Table 1 Properties of particles used in the DEM simulations

Properties	Symbol	Unit	Value
Density	ρ	kg/m ³	2650
Young's modulus	E	MPa	200
Shearing stiffness coefficient	ν	—	0.3
Friction angle	φ'_c	°	19
Rolling stiffness coefficient	α_r	—	0.8
Twisting stiffness coefficient	α_{tw}	—	0.8
Rolling resistance coefficient	η_r	—	0.15
Twisting resistance coefficient	η_{tw}	—	0.15
Cohesive strength	σ_{coh}	kPa	50, 100, 200

2.3 Undrained cyclic loading scheme

The uncemented specimens and cemented specimens are subjected to undrained cyclic loadings. The cyclic loading is applied by moving the top wall at a constant velocity,

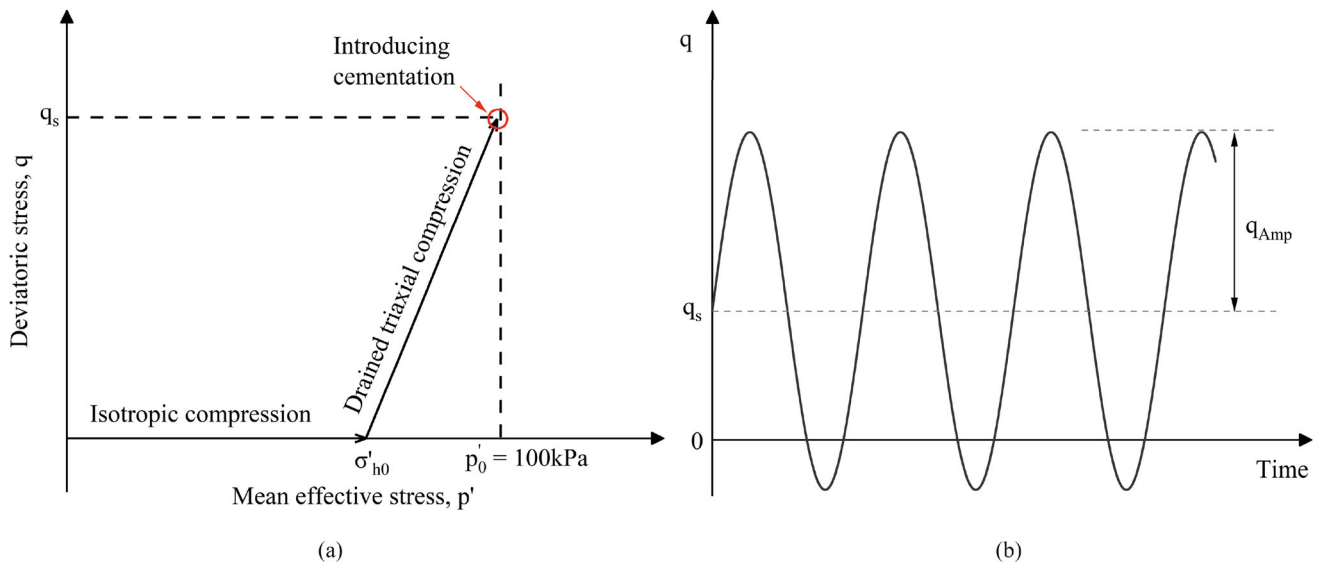


Fig. 2 Illustration of **a** the initial static shear process and **b** cyclic loading condition

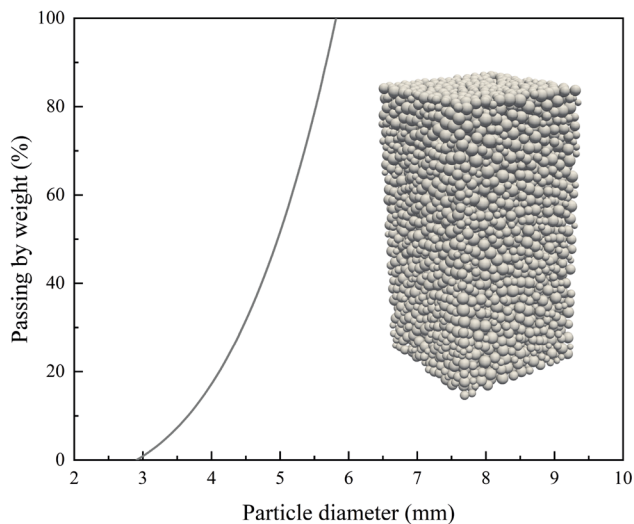


Fig. 3 Particle size distribution of the DEM sample. $D_{50} = 4.97$ mm

while the four lateral walls are controlled to move correspondingly to keep the sample volume constant to mimic the undrained condition. The bottom wall is fixed. The moving direction of the top wall reverses as long as the deviatoric stress (q) reaches the predefined maximum or minimum value, i.e. $q_s \pm q_{Amp}$, as illustrated in Fig. 2b, where q_{Amp} is the applied deviatoric stress amplitude. All simulations presented in this study have $q_s - q_{Amp} < 0$, corresponding to the reversal cyclic test condition [16]. Future studies are recommended to investigate the cyclic response of initial-sheared cemented sand under non-reversal cyclic loading conditions.

The cyclic amplitude can also be described by the cyclic stress ratio (CSR), defined as $CSR = \frac{q_{Amp}}{2p'_0}$. The deviatoric

stress (q), mean effective stress (p') and pore pressure (u) are defined as: $q = \sigma'_v - \sigma'_h$, $p' = (\sigma'_v + 2\sigma'_h)/3$, $u = p'_0 - p'$, respectively [8]. During the simulation, the unbalanced force, which is defined as the ratio of mean summary force on bodies and mean force magnitude on interactions, is below 5×10^{-4} for ensuring a quasi-static loading condition [36]. The onset of liquefaction (also referred to as initial liquefaction) is defined when the pore pressure ratio ($r_u = u/p'_0$) reaches 1. This is equivalent to the mean effective stress reducing to zero. At this state, bonds are extensively broken and can no longer provide effective structural support. Since $p'_0 = 100$ kPa for all specimens in this study, liquefaction occurs when the pore pressure reaches 100 kPa. This pore pressure-based criterion is widely adopted in the literature [13, 39].

3 Macroscopic mechanical behaviour

In this section, the undrained cyclic triaxial response of cemented specimens with different cementation levels, CSR and SSR are investigated. The simulation results of the uncemented specimens are also presented for comparison. Since this study focuses on the pre-liquefaction behaviour and liquefaction resistance of cemented sands, the cyclic loading is terminated when the specimens reach their liquefaction states.

3.1 Undrained cyclic response

Figure 4 presents the undrained cyclic responses of uncemented specimens with various levels of initial static shear stress. For the sample with SSR=0, as shown in Fig. 4a, it

Table 2 Summarised information of DEM specimens subjected to various test conditions

Cementation σ_{coh} (kPa)	σ'_{v0} (kPa)	σ'_{h0} (kPa)	q_s (kPa)	SSR (–)	CSR (–)
0	100	100	0	0	0.25, 0.28, 0.3, 0.33, 0.35
50	100	100	0	0	0.3, 0.35, 0.5
100	100	100	0	0	0.3, 0.33, 0.35, 0.38, 0.4, 0.5
200	100	100	0	0	0.3, 0.35, 0.4, 0.43, 0.44, 0.45, 0.5
0	106.66	96.66	10	0.05	0.25, 0.28, 0.3, 0.33, 0.35
50	106.66	96.66	10	0.05	0.3, 0.33, 0.35, 0.5
100	106.66	96.66	10	0.05	0.3, 0.33, 0.35, 0.38, 0.4, 0.5
200	106.66	96.66	10	0.05	0.3, 0.35, 0.4, 0.43, 0.45, 0.5
0	113.33	93.33	20	0.1	0.25, 0.28, 0.3, 0.33, 0.35
50	113.33	93.33	20	0.1	0.3, 0.33, 0.35, 0.5
100	113.33	93.33	20	0.1	0.3, 0.33, 0.35, 0.5
200	113.33	93.33	20	0.1	0.3, 0.35, 0.4, 0.43, 0.45, 0.47, 0.5
0	120	90	30	0.15	0.25, 0.28, 0.3, 0.33, 0.35
50	120	90	30	0.15	0.3, 0.33, 0.35, 0.5
100	120	90	30	0.15	0.25, 0.3, 0.33, 0.35, 0.5
200	120	90	30	0.15	0.3, 0.35, 0.4, 0.5
0	130	85	45	0.225	0.25, 0.28, 0.3, 0.33, 0.35
50	130	85	45	0.225	0.3, 0.33, 0.35, 0.5
100	130	85	45	0.225	0.25, 0.3, 0.33, 0.35, 0.5
200	130	85	45	0.225	0.3, 0.35, 0.4, 0.5

is subjected to symmetrical cyclic deviatoric stress. During the cyclic loading, the pore pressure is built up gradually. Meanwhile, the effective stress is continuously decreased. After around 10 cycles, the pore pressure increases abruptly, and the mean stress decreases rapidly. Eventually, the pore pressure builds up to 100 kPa, and the deviatoric stress and the mean effective stress reduce to zero, indicating the onset of liquefaction. A flow-type failure mode can be identified for this sample, as the strain developed slightly at the beginning, while a significant deformation occurs just before liquefaction.

The cyclic responses of uncemented specimens with the presence of initial shear stress are shown in Fig. 4b–d. The specimens undergo asymmetric cyclic loading in these cases. For the uncemented sample with a low SSR, as shown in Fig. 4b, its cyclic behaviour and failure mode are similar to those not experiencing initial static shear. It is worth noting that it shows a slight increase (from 12 to 13) in the number of cycles to liquefaction. Comparing Fig. 4c and d to a, it can be found that as the level of initial static shear stress (SSR) increases, the pore pressure builds up more rapidly during the first two cycles, and a lower number of cycles is needed to trigger the liquefaction. Namely, the presence of a light initial static shear stress is beneficial to liquefaction resistance. However, as SSR increases, the presence of initial static shear stress tends to

reduce the liquefaction resistance. This finding aligns with that reported in Harder and Boulanger [11], as also pointed out in Yang and Sze [47]. They reported that the effect of initial static shear stress is negative for loose sand under the condition that the effective confining pressure is less than about 300 kPa and SSR is below 0.3. Yang and Sze [47] and Yang and Pan [50] further established the effect of SSR and reported that the presence of initial static shear stress is beneficial to the liquefaction resistance of loose sand at a low level of the initial shear stress, but it becomes detrimental at high SSR levels. A critical SSR of 0.1 was reported by Yang and Pan [50]. The simulation conditions presented in Fig. 4 fall within the conditions Yang and Pan [50] outlined. Moreover, the presence of initial static shear stress changes the failure mode. It can be observed from the stress–strain relationship in Fig. 4c that the strain develops gradually and only occurs in one direction, which is characterised as cyclic mobility. As SSR increases, such behaviour becomes more pronounced, as shown in Fig. 4d.

Figure 5 shows the undrained cyclic responses of cemented specimens with $\sigma_{coh} = 100$ kPa. Apparently, the introduction of cementation greatly enhances the liquefaction resistance compared to the corresponding uncemented sample shown in Fig. 4, indicating that the effect of cementation on liquefaction resistance is always beneficial. For the cemented sample without initial static shear (i.e.

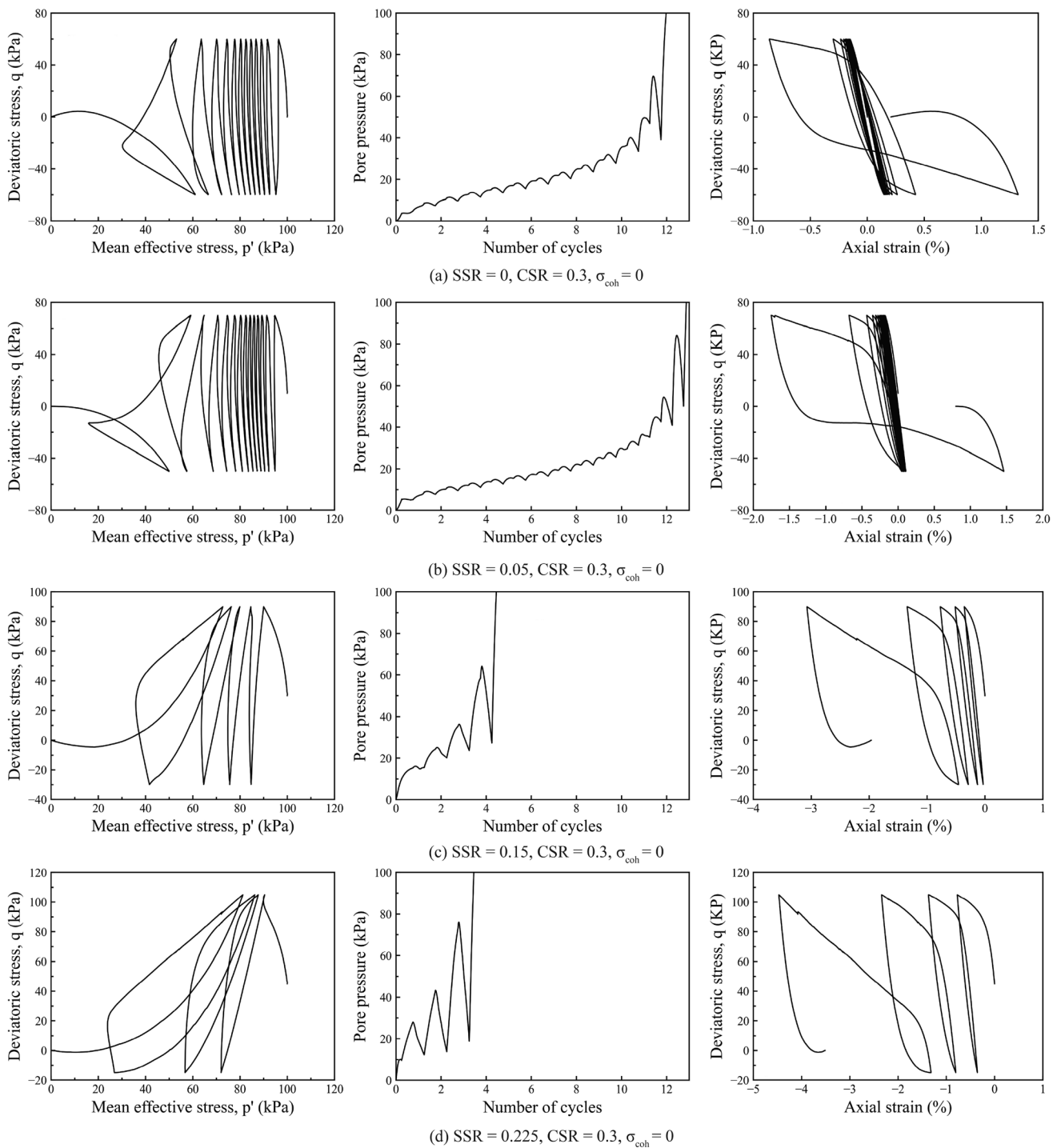


Fig. 4 Undrained cyclic response: (left) stress path, (middle) evolution of pore pressure with cyclic number and (right) evolution of deviatoric stress with axial strain of uncemented specimens ($\sigma_{coh} = 0$) with $CSR=0.3$ and **a** $SSR=0$, **b** $SSR=0.05$, **c** $SSR=0.15$ and **d** $SSR=0.225$

$SSR=0$), as shown in Fig. 5a, it takes around 52 cycles for the pore pressure to gradually build up to 10% of the initial mean effective stress. During this process, the mean effective stress progressively decreases, and the axial strain cyclically changes in a limited range. It is during the final several cycles that the pore pressure abruptly increases,

leading to sample liquefaction. The introduction of cohesion does not change the failure mode, as a similar stress–strain response can be observed in the corresponding uncemented sample shown in Fig. 4. For the cemented sample with a low SSR ($SSR=0.05$), an obvious enhancement in liquefaction resistance can be observed due to the

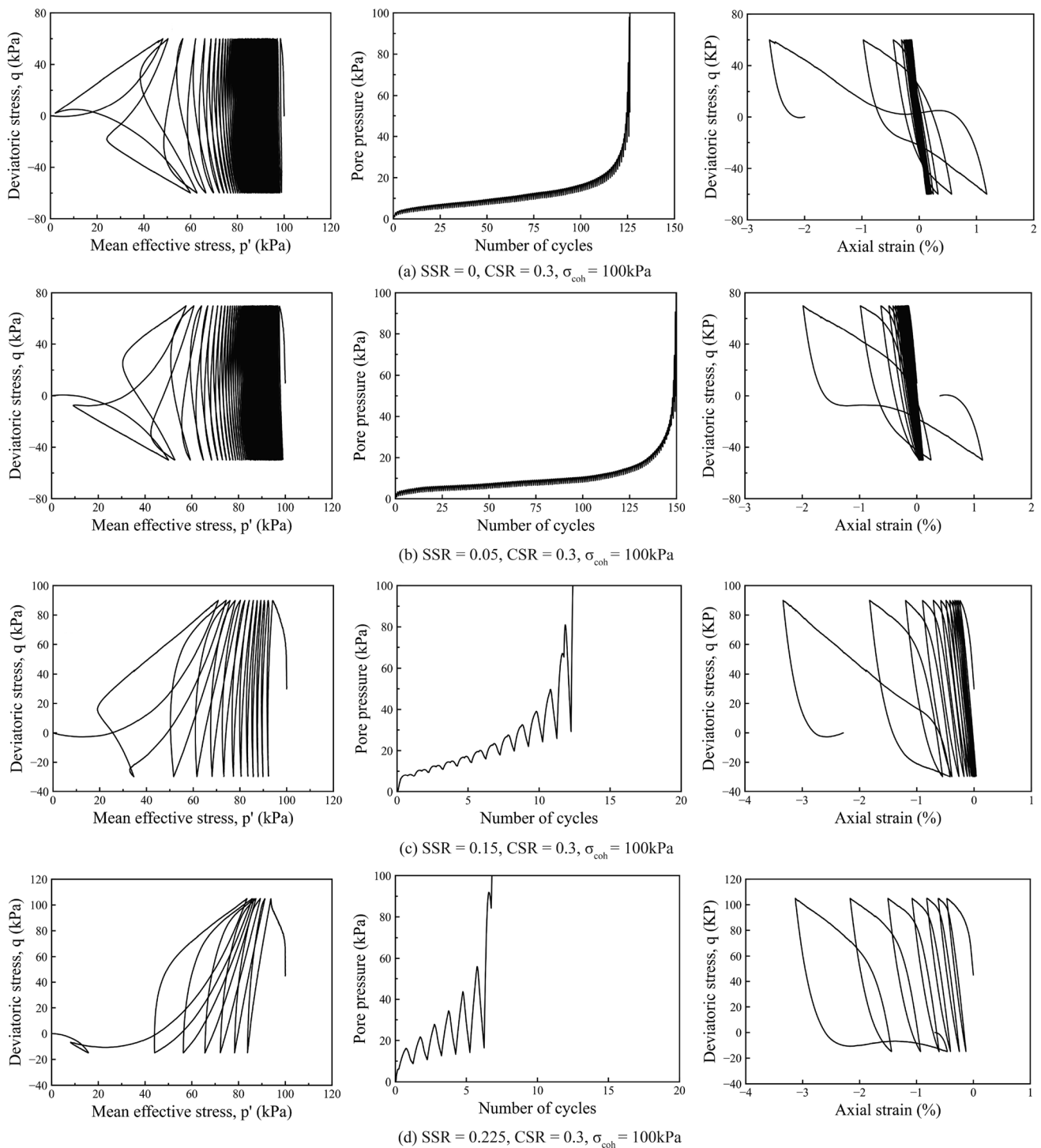


Fig. 5 Undrained cyclic response: (left) stress path, (middle) evolution of pore pressure with cyclic number and (right) evolution of deviatoric stress with axial strain of cemented specimens ($\sigma_{coh} = 100$ kPa) with $CSR=0.3$ and **a** $SSR=0$, **b** $SSR=0.05$, **c** $SSR=0.15$ and **d** $SSR=0.225$

combined beneficial effect of SSR and cementation. In contrast, a large decrease in the number to trigger liquefaction can be observed in Fig. 5c and d compared to Fig. 5a, suggesting a large SSR is detrimental to the liquefaction resistance of cemented specimens.

The undrained cyclic responses of cemented specimens with a higher cementation level ($\sigma_{coh} = 200$ kPa) are presented in Fig. 6. The simulations terminate when the number of cycles reaches 140, at which point the sample is still far from liquefaction. For the case with $SSR=0$, the mean effective stress almost remains constant,

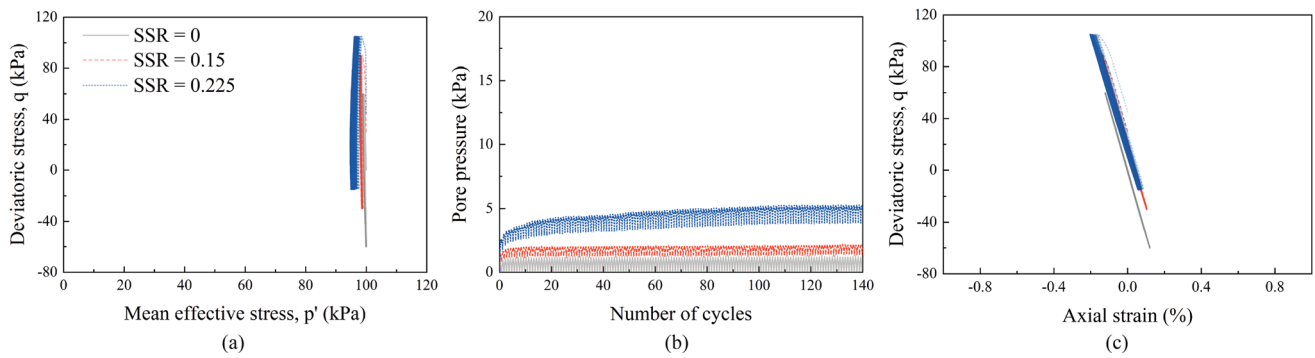


Fig. 6 Effect of SSR on the undrained cyclic response of cemented specimens with $\sigma_{coh} = 200$ kPa and $CSR = 0.3$: **a** stress path, **b** evolution of pore pressure with cyclic number and **c** evolution of deviatoric stress with axial strain

characterised as a vertical line in Fig. 6a. Negligible pore pressure is developed during the cyclic loading. The stress–strain relationship shows as a straight line as well, with a maximum axial strain of 0.12%. This indicates a non-liquefiable state. For cemented specimens with a higher SSR presented in Fig. 6, more pore pressure is built up, although it remains at a low value, in the first few cycles as SSR increases. Consequently, the mean effective stress reduces in the first few cycles. As cyclic loading progresses after the first few cycles, the pore pressure and the mean effective stress exhibit negligible change.

3.2 Liquefaction resistance

To demonstrate the effect of cementation on the liquefaction resistance, Fig. 7 plots the number of cycles upon liquefaction (N_f) of cemented specimens under various CSR. Data obtained from experimental tests [45] are also included for comparison. Note that $SSR = 0$ for the specimens presented in Fig. 7. It can be seen that the DEM results capture the effects of CSR and cementation reported from the literature. Specifically, a higher CSR leads to a lower N_f , indicating that liquefaction is easier to trigger under a high cyclic stress amplitude. The presence of

cementation strengthens the resistance to liquefaction, and this resistance increases with the degree of cementation. In addition, the $CSR-N_f$ relationship is fitted by a power-law empirical equation [45], which is described in Eq. (13).

$$CSR = aN_f^{-b} \quad (13)$$

Figure 7 shows that the DEM results align closely with the data from Xiao et al. [45], as evidenced by their overlapping trend lines in cases with $m_c \leq 6.7\%$. This also implies the studied range of σ_{coh} can represent practical cementation amounts observed in experiments, confirming the estimation in Sect. 2.1. This agreement between numerical simulations and laboratory experiments validates the presented modelling approach, demonstrating that the developed DEM model enables not only phenomenological investigation of cementation effects but also quantitative assessment of how different cementation levels influence the liquefaction behaviour. It should be noted that the liquefaction resistance of DEM specimens increases as σ_{coh} increases from 100 kPa to 200 kPa, while this trend is less pronounced as m_c increases from 6.7% to 9.9% in Xiao et al. [45]. This may be attributed to the fact that increasing calcite content does not necessarily translate to proportional enhancement in mechanical properties. As revealed by SEM images in Xiao et al. [45], carbonate precipitation was found to coat sand grain surfaces and bond grain contacts. These different distribution patterns contribute differently to mechanical improvement, with surface coating providing negligible enhancement [53]; thus, increases in carbonate content may not always result in corresponding increases in mechanical strength.

The combined effect of cementation and SSR on the liquefaction resistance is shown in Fig. 8. The effect of cementation on specimens with the presence of initial static shear stress is identical to what is observed in specimens with $SSR = 0$ (Fig. 7), though it's worth noting that the $CSR-N_f$ trend line becomes steeper as SSR increases,

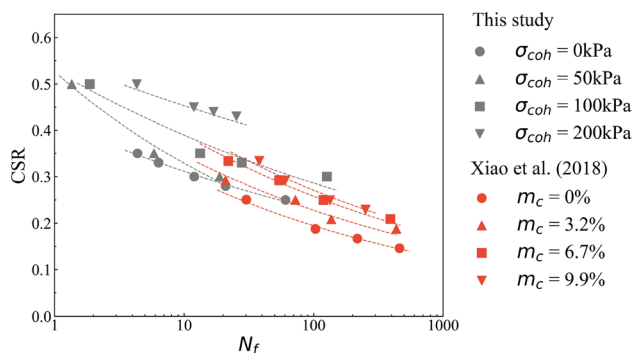


Fig. 7 Comparison of DEM results (this study) with experimental results on $CSR-N_f$ relationship. m_c is the mass fraction of carbonate in Xiao et al. [45]

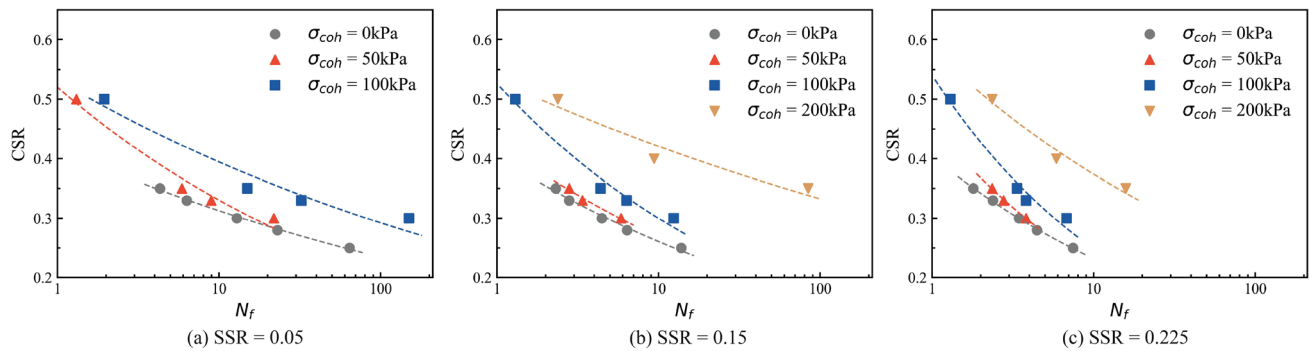


Fig. 8 Effect of cementation on the number of cycles to trigger liquefaction (N_f): **a** SSR=0.05; **b** SSR=0.15 and **c** SSR=0.225

Table 3 Summarisation of the fitted parameters

SSR	σ_{coh} (kPa)	a	b	R^2
0	0	0.420	0.130	0.992
	50	0.527	0.205	0.980
	100	0.530	0.134	0.942
	200	0.566	0.088	0.982
0.05	0	0.417	0.125	0.996
	50	0.520	0.197	0.972
	100	0.532	0.130	0.944
0.15	0	0.404	0.190	0.986
	50	0.428	0.203	0.979
	100	0.526	0.244	0.975
	200	0.532	0.102	0.927
0.225	0	0.404	0.241	0.998
	50	0.458	0.317	0.998
	100	0.540	0.337	0.975
	200	0.523	0.193	0.975

R^2 : coefficient of determination

suggesting a decrease in liquefaction resistance under a high SSR value.

To quantify the effect of cementation and SSR on cyclic resistance, all data are fitted using Eq. (13). The fitted parameters, namely, a , b in Eq. (13), are summarised in Table 3. The parameter a indicates the CSR that leads to liquefaction in a single cycle ($N_f=1$), thus a higher value of a suggests a higher liquefaction resistance. The parameter b describes the change rate of CSR with increasing number of cycles. The correlations between parameters a and b with cementation content (m_c) and SSR are plotted in Fig. 9. It can be seen from Fig. 9a that parameter a shows a linear relationship with m_c , while SSR has minimal influence on this relationship. Figure 9b indicates that parameter a is independent of SSR. Parameter b is affected by both cementation content and SSR as shown in Fig. 9c and d, where parameter b exhibits a quadratic relationship with

m_c , and an exponential relationship with SSR. Based on these observations, Eq. (14) and Eq. (15) are proposed as follows.

$$a = k_1 m_c + k_0 \quad (14)$$

$$b = (k_2 m_c^2 + k_3 m_c + k_4) \times e^{k_5 SSR} \quad (15)$$

where a and b are the parameters in Eq. 13, k_i ($i = 0-5$) are fitted parameters. m_c is the mass fraction of cementation and SSR is the initial static shear stress. By integrating Eq. (14) and Eq. (15) into Eq. (13), the soil liquefaction resistance described by the number of cycles to liquefaction (N_f) is established as a function of CSR, SSR and m_c . Future experimental studies on initial-sheared cemented soils are recommended as to calibrate the proposed empirical equation.

Figure 10a shows the effect of initial static shear stress (SSR) on the liquefaction resistance of cemented specimens. All the specimens presented in Fig. 10 have the same σ_{coh} of 100 kPa. The effect of SSR, either beneficial or detrimental, can thus be easily identified in Fig. 10a. Using the case of SSR=0 as a reference, the curve shifts to the right for the case of SSR=0.05, indicating an increase in N_f . As SSR increases, the curves shift to the left side, suggesting the detrimental effect increases as SSR increases. Furthermore, the magnitude of the effect of SSR depends on CSR, which is highlighted in Fig. 10b. To demonstrate the change in liquefaction resistance, N_f is normalised which is defined as $\frac{N_f^{SSR=0} - N_f}{N_f^{SSR=0}}$, where $N_f^{SSR=0}$ represents the N_f for the sample without initial static shear stress and N_f for the case with SSR = 0.05, 0.15 or 0.225. Thus, a positive normalised N_f represents a detrimental effect and the higher the value, the more significant the detrimental effect, as shown in Fig. 10b. While a negative normalised N_f represents a beneficial effect. It can be seen in Fig. 10b that both the beneficial and detrimental effects are more pronounced at a low CSR, and they decrease linearly as CSR increases.

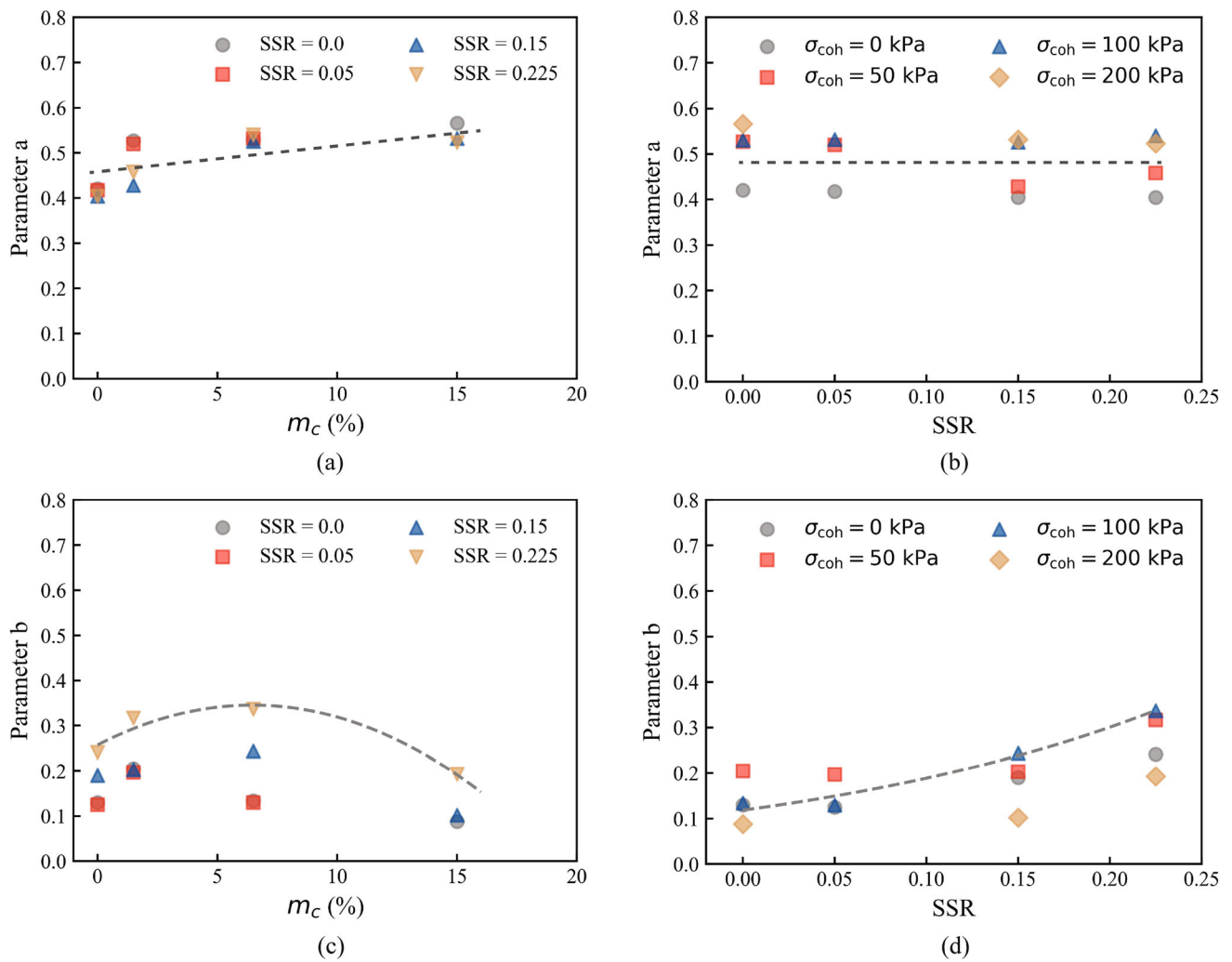


Fig. 9 Correlation between parameter a and b of Eq. (13) with carbonate content (m_c) and SSR, respectively. The dashed line is the trending line

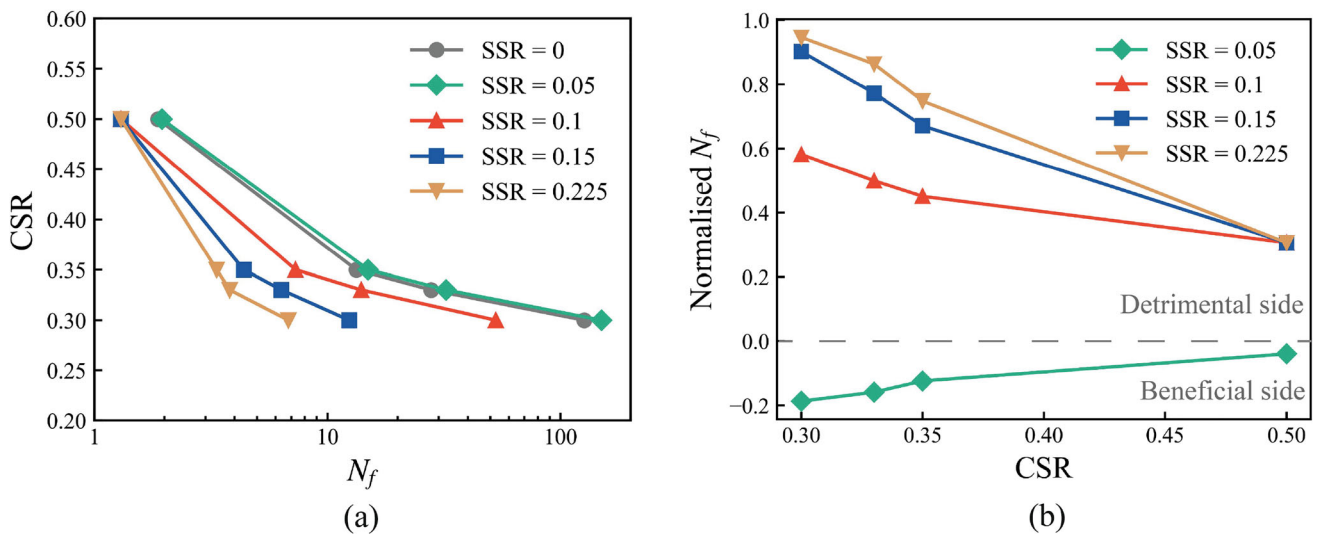


Fig. 10 **a** Effect of initial static shear stress (SSR) on the number of cycles to trigger liquefaction (N_f); **b** Evolution of normalised N_f with CSR. $\sigma_{coh} = 100$ kPa for specimens presented herein

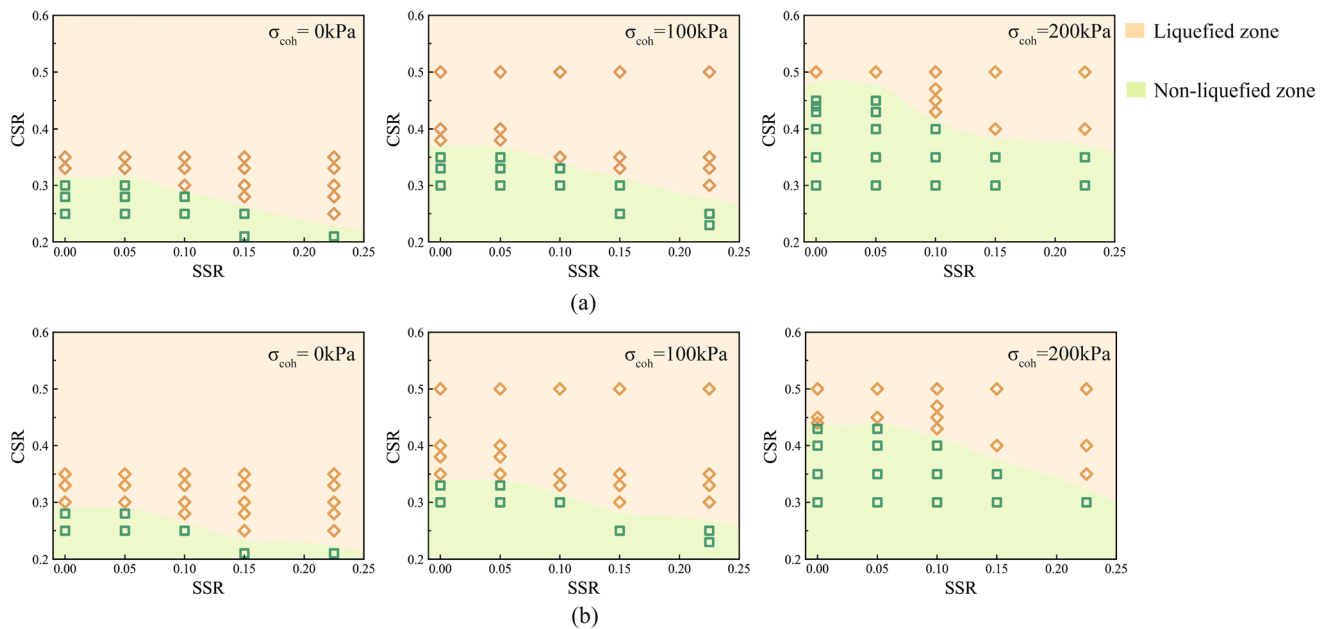


Fig. 11 Liquefaction status after a given number of cycles (N_f^*): **a** $N_f^* = 10$; **b** $N_f^* = 20$. The green square symbol represents not-yet-liquefied status, the yellow diamond symbol represents the liquefied status

The combined effect of CSR, SSR and cementation on the cyclic resistance is further elaborated in Fig. 11. In Fig. 11, each symbol represents a single simulation in which liquefaction either occurs or does not within a given number of cycles (N_f^*). The two areas, namely, the liquefaction zone and the not-yet liquefied zone, can thus be estimated. It is clear to see that the not-yet-liquefied zone gradually increases as cementation content increases. This figure is a supplement to Figs. 8 and 10, which show the number of cycles to liquefaction (N_f). In engineering scenarios such as the extraction of aged piles (cementation may present [5]) by the vibratory method, it is also good to know the number of cycles needed to trigger liquefaction. Such information can then be inferred from the diagram shown in Fig. 11.

3.3 Bond breakage behaviour

The effect of σ_{coh} , SSR and CSR on bond breakage behaviour is illustrated in Fig. 12a–c, respectively. The bond breakage ratio, defined as the ratio of the number of broken bonds to the total number of bonds, is used to describe the bond breakage progress during cyclic loading. In general, a higher cementation leads to less bond breakage given the same number of cycles. Notably, bond breakage becomes negligible at high cementation ($\sigma_{coh}=200$ kPa), corresponding to a non-liquefied state as shown in Fig. 6. Additionally, an increase in SSR (except SSR=0.05) or CSR can lead to a greater extent of bond breakage under the same cyclic loading conditions. It can also be inferred from Fig. 12 that the bond breakage behaviour exhibits a stepwise incremental pattern, which has also been observed in Zhang et al. [57] Specifically, the breakage ratio

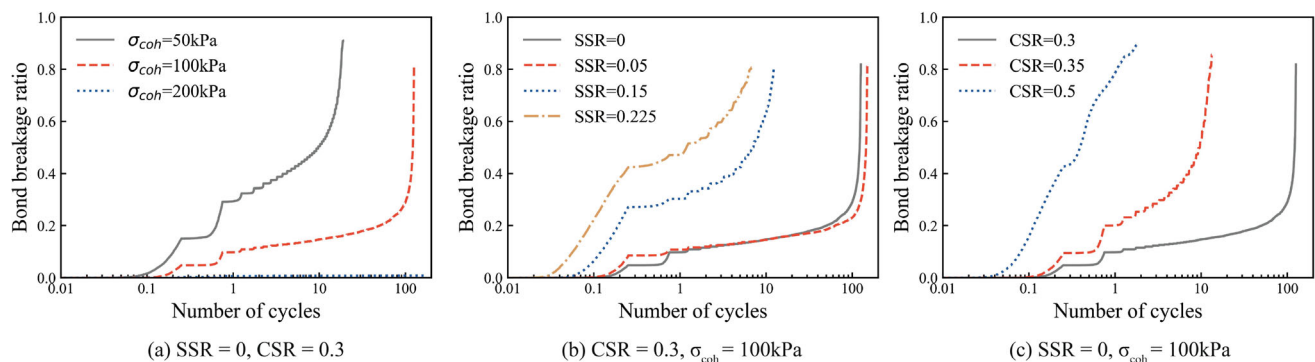


Fig. 12 Effect of **a** cementation level (σ_{coh}), **b** SSR and **c** CSR on the evolution of bond breakage ratio with the number of cycles

increases during the first quarter of each cycle, followed by a plateau in the second quarter, it rises again in the third quarter and remains constant in the final quarter. Such an evolution pattern repeats in the following cycles until reaching the liquefaction state. Furthermore, a major breakage occurs during the first cycle. For instance, for the case with $SSR=0.225$, $CSR=0.3$ and $\sigma_{coh}=100$ kPa, 47% of bonds broken in the first cycle, occupying 59% of the total bond breakage ratio. Moreover, this breakage intensity in the first cycle is affected by σ_{coh} , SSR and CSR . A high σ_{coh} can significantly reduce the bond breakage in the first cycle, while a high SSR or CSR leads to more severe bond breakage in the first cycle.

The dominant first-cycle bond breakage influences the macroscopic mechanical response, as particles lose the structural support that was resisting the applied external stress. Without this bond resistance, the applied stresses tend to compact particles. This tendency is prevented under the undrained condition, manifesting as the rapid pore pressure buildup observed in the macroscopic mechanical behaviour.

Since a major breakage occurs in the first cycle, the density distribution of broken bonds at the end of the first cycle is presented to investigate the spatial distribution of the bond breakage behaviour. Figure 13 compares the density distribution of broken bonds for cemented specimens under different conditions. It can be observed that for the cemented sample with low cementation (Fig. 13a), bond breakage is uniformly distributed throughout the sample. In contrast, higher cementation results in a less uniform distribution of bond breakage (Fig. 13b). For other specimens presented in Fig. 13, they demonstrate uniform breakage distribution, independent of the change in SSR or CSR . This finding is in agreement with observations by Zhang et al. [57], in which a uniform bond breakage was observed in the DEM cemented sample.

4 Microstructural analysis

In this section, microscopic analysis is conducted, from the point of view of coordination number and fabric anisotropy, to understand the combined effect of cementation and initial static shear stress on the microstructural response of granular soils under cyclic loadings.

4.1 Coordination number

The coordination number (Z) characterises the average contacts per particle and has been widely used to describe the structural connectivity of granular materials [39, 53]. It is defined as:

$$Z = \frac{2N_c}{N_p} \quad (16)$$

where N_c is the number of inter-particle contacts, and N_p is the number of particles.

Figure 14 compares the evolution of Z of specimens with various σ_{coh} and subjected to different SSR and CSR during cyclic loading. For the sake of comparison, Z is plotted against the normalised cyclic number (N/N_f). In general, it can be observed that the coordination number gradually decreases as the cyclic loading progresses for all the specimens, which eventually reach liquefaction. This implies a continuous loss of inter-particle contacts during cyclic loading. The coordination number drops to a value below 2 when the sample approaches the liquefaction state, suggesting an unstable structure upon liquefaction since an individual particle can not be stable given less than 2 contacts in a 3D granular system. The effect of σ_{coh} can be inferred from Fig. 14a, a positive effect of cementation in preventing contact loss is evident. This indicates that the microscopic mechanism underlying cementation-enhanced liquefaction resistance is primarily the prevention of

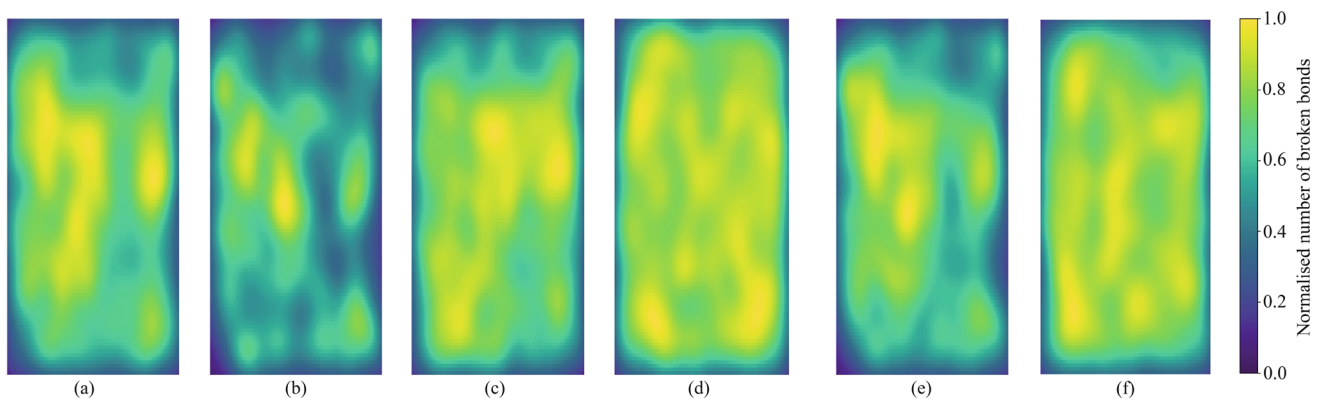


Fig. 13 Density distribution of broken bonds at the end of the 1st cycle, projection on X-Y plane: **a** $SSR=0$, $CSR=0.3$, $\sigma_{coh}=50$ kPa; **b** $SSR=0$, $CSR=0.3$, $\sigma_{coh}=100$ kPa; **c** $SSR=0.15$, $CSR=0.3$, $\sigma_{coh}=100$ kPa; **d** $SSR=0.225$, $CSR=0.3$, $\sigma_{coh}=100$ kPa; **e** $SSR=0$, $CSR=0.35$, $\sigma_{coh}=100$ kPa; **f** $SSR=0$, $CSR=0.5$, $\sigma_{coh}=100$ kPa

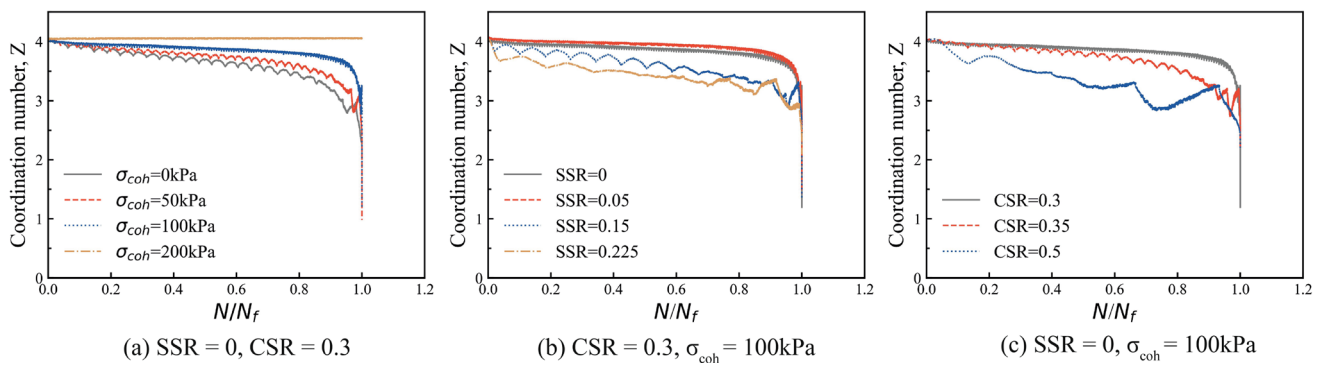


Fig. 14 Effect of **a** cementation level (σ_{coh}), **b** SSR and **c** CSR on the evolution of coordination number with the normalised number of cycles

contact loss. In addition, the introduction of initial static shear stress leads to a more severe loss in inter-particle contacts, and this detrimental effect is more pronounced at a higher SSR (Fig. 14b). The same trend is also observed in terms of the effect of CSR as shown in Fig. 14c.

4.2 Fabric anisotropy

The macroscopic behaviour of granular material is not only associated with the average contact number but also the arrangement of the particles [18, 51, 61]. Such a property is often characterised by fabric tensors [1, 52, 59, 60]. In this study, the contact normal-based fabric tensor [25, 31] is adopted to describe the fabric and hence quantify the fabric anisotropy. The fabric tensor ϕ_{ij} is calculated by:

$$\phi_{ij} = \frac{1}{N_c} \sum_{c=1}^{N_c} n_i^c n_j^c \quad (17)$$

where N_c is the number of inter-particle contacts, and n^c is the unit contact normal vector. Multiple scalar variables have been proposed to describe the fabric anisotropy [1, 9]. In this study, the scalar variable proposed by Barreto and O'Sullivan [1] is used to quantify the fabric anisotropy (ϕ_d). It is defined as:

$$\phi_d = \frac{1}{\sqrt{2}} \left[(\phi_1 - \phi_2)^2 + (\phi_2 - \phi_3)^2 + (\phi_1 - \phi_3)^2 \right]^{1/2} \quad (18)$$

where ϕ_1 , ϕ_2 and ϕ_3 are the principal values of the fabric tensor ϕ_{ij} . This definition of ϕ_d reduces to $\phi_1 - \phi_3$ for axisymmetric conditions.

Figure 15 presents the evolution of fabric anisotropy with the normalised number of cycles. All the specimens demonstrate a low fabric anisotropy at the beginning of the cyclic loading, while it increases either gradually or abruptly when approaching the liquefaction state. For the uncemented sample without being subjected to initial static shear (Fig. 15a), ϕ_d increases gradually in a cyclic pattern. With the introduction of cementation, the variation of ϕ_d is constrained during the cyclic loading, and its evolution pattern transitions from a gradual mode to an abrupt mode as cementation increases. For specimens subjected to initial static shear (Fig. 15b), ϕ_d increases in a gradual manner and exhibits a larger variation as SSR increases. Figure 15c indicates that as CSR increases, the evolution of fabric anisotropy transitions to a more gradual pattern, with the magnitude of variation in fabric anisotropy also increasing. Consequently, the evolution of fabric anisotropy, including the variation magnitude and the development pattern, is affected by cementation level, SSR and CSR.

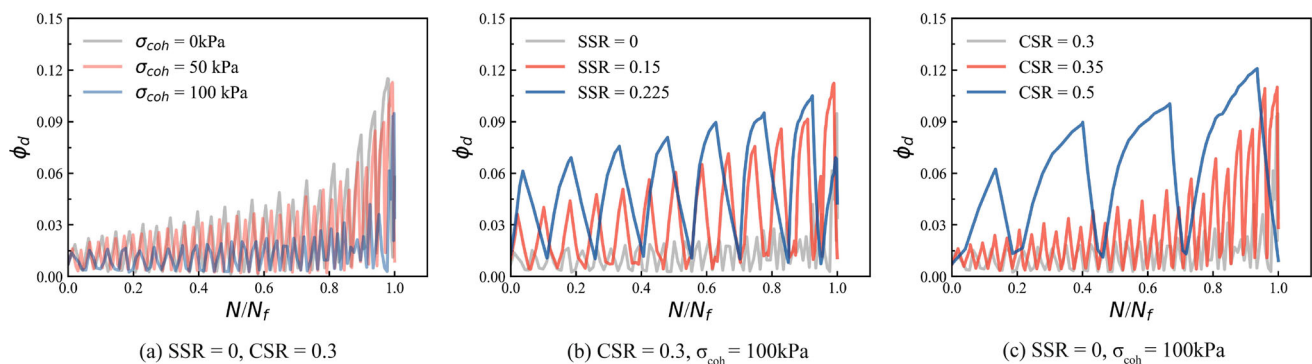


Fig. 15 Effect of **a** cementation level (σ_{coh}), **b** SSR and **c** CSR on the evolution of fabric anisotropy with the normalised number of cycles

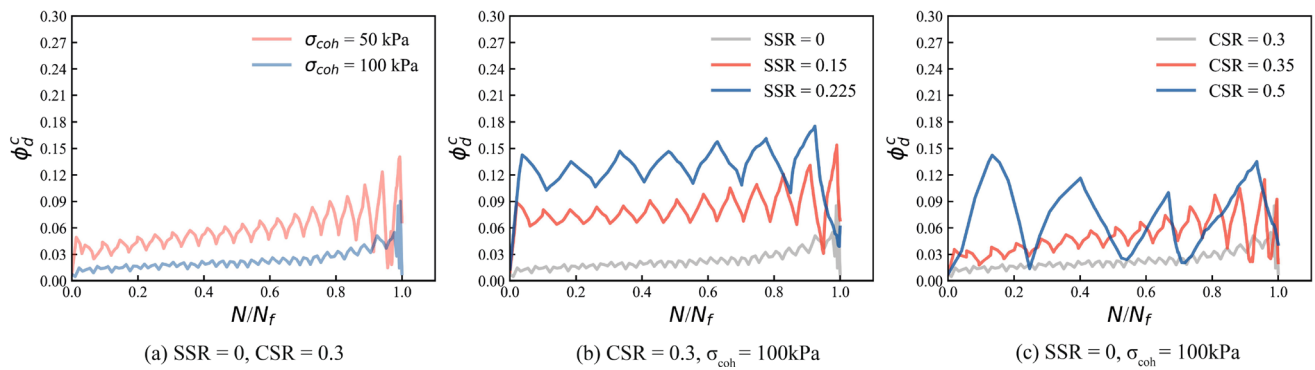


Fig. 16 Effect of **a** cementation level (σ_{coh}), **b** SSR and **c** CSR on the evolution of fabric anisotropy of cemented contacts with the normalised number of cycles

The fabric anisotropy of the soil skeleton is quantified by ϕ_d . Similarly, the fabric anisotropy of cementation (ϕ_d^c) can be derived by considering only the cemented contacts in Eq. (17). Figure 16 presents the evolution of fabric anisotropy of cementation with the normalised number of cycles. In general, the cementation anisotropy shows an increasing trend with the number of cycles in all specimens. It can be seen that a higher cementation level results in consistently lower fabric anisotropy compared to a lower cementation, while increased SSR and CSR intensify fabric anisotropy throughout the loading process. This fabric evolution behaviour reveals the microscopic mechanism underlying liquefaction resistance differences. High fabric anisotropy indicates contacts are preferentially oriented, leading to directional strength variation. In contrast, low fabric anisotropy provides relatively uniform strength in all directions. Consequently, during cyclic loading with stress reversal, specimens with low fabric anisotropy (higher σ_{coh} or lower SSR) exhibit higher liquefaction resistance.

5 Conclusions

In engineering scenarios where cementation develops in soils that have previously undergone initial static shear, both cementation and initial static shear stress jointly affect the soil behaviour on subsequent cyclic loading. However, their combined effect was insufficiently understood. Gaining insight into this interaction is essential for practical applications, such as non-invasive cementation treatments for soils beneath structures and the natural precipitation of cementation around offshore wind piles. To fill this knowledge gap, this study employs three-dimensional DEM to investigate the interplay between cementation and initial static shear stress. Cementation levels are systematically varied to represent realistic conditions ranging from light to heavy cementation. DEM specimens with different combinations of cementation and static shear

stress ratio (SSR) are then subjected to undrained cyclic loading across a wide range of cyclic stress ratios (CSR). The major findings of this study are as follows:

- The introduction of cementation consistently enhances liquefaction resistance, regardless of the presence or magnitude of SSR. Moreover, the effectiveness of cementation increases with its level. The DEM results align well with experiments conducted without an initial SSR, allowing not only a phenomenological investigation of cementation effects but also a quantitative assessment of how varying cementation levels influence liquefaction behaviour.
- The liquefaction resistance of the cemented sample depends on both CSR and SSR. Notably, the effect of SSR, whether beneficial or detrimental, is more pronounced at a low CSR, and it decreases linearly as CSR increases.
- A new empirical equation is proposed to describe the relationship between the number of cycles to liquefaction (N_f) with CSR, cementation level and SSR. This equation extends the widely used form ($CSR = aN_f^{-b}$) by incorporating cementation level and SSR, representing the first framework to simultaneously account for their coupled effects. This provides a practical tool for optimising ground improvement strategies and facilitating vibratory extraction of aged pile foundations.
- Bond breakage in cemented specimens occurs in a stepwise pattern during cyclic loading, with significant breakage occurring in the first cycle. The extent of bond breakage is strongly influenced by cementation level, SSR, and CSR. While cementation mitigates bond breakage, increasing SSR or CSR intensifies it.
- Micromechanical analysis reveals that cementation helps maintain inter-particle contacts, contributing to a more stable soil structure under cyclic loading. In contrast, SSR promotes contact loss and reduces structural stability. Additionally, fabric anisotropy

evolves during cyclic loading, with its magnitude and progression (gradual or abrupt) being affected by cementation level, SSR, and CSR.

This study provides valuable insights into the combined effects of cementation and initial static shear stress on the cyclic behaviour of soil. The findings provide practical guidance for engineering applications such as vibratory extraction of aged piles and contribute to the development of multiscale constitutive models for cemented soils under cyclic loading conditions. Future research is suggested to consider the effect of cementation homogeneity, as practical cementing processes often result in non-uniform distributions [26, 29] that may significantly influence liquefaction resistance and failure mechanisms. Investigations using realistic particle shapes are also recommended to assess particle shape effects on cyclic behaviour of cemented soils.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no Conflict of interest.

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