

Preliminary Results on Cyclic Degradation and Pore Pressure Generation in Sand-Fine Mixtures

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ABSTRACT: The dynamic response of sand-kaolin mixtures under low confining stresses is essential for a thorough understanding of soil behavior in geotechnical earthquake engineering, especially in seismic regions. The influence of fine particles has a significant impact on soil stability as it affects degradation and the generation of pore water pressure under cyclic loading. While the role of fine particles in filling voids and altering pore structure is recognized, their specific effects on the degradation index and pore water pressure dynamics under changing stresses are still poorly understood. In this study, the effects of fine particle content and confining stress on the degradation index and the build-up of pore water pressure in sand-kaolin mixtures are investigated. To investigate these factors, a series of cyclic triaxial tests were conducted under undrained conditions. The results show that an increase in the kaolinite content changes the degradation behavior and leads to a faster degradation of the soil structure at lower confining stresses. In addition, a higher proportion of kaolinite reduces the faster generation of pore water pressure. These results underline the crucial role of fine particles and confining stress in influencing the dynamic behavior of the soil under seismic loading. The results of this research provide a better understanding of the complex behavior of such mixtures in earthquake-prone regions and provide a solid basis for further investigation of the complex interactions between kaolinite clay and sand under cyclic loading.

KEYWORDS: sand-fine mixtures, kaolinite clay, degradation index, normalized pore water pressure.

1 INTRODUCTION

Understanding the dynamic behavior of granular soils under cyclic loading is essential for improving seismic geotechnical design, especially in earthquake-prone areas. Among these materials, sand-fines mixtures, particularly those with clayey fines like kaolinite, pose significant challenges in predicting pore water pressure buildup and stiffness degradation. Their behavior is influenced not just by their fabric and fines content but also by confining stress levels and cyclic strain amplitudes, which impact liquefaction potential, dilatancy, and degradation trends. The role of fines in influencing the response of sandy soils under seismic loading has been widely recognized. Classical studies by Seed (2010), Lade, Liggio and Yamamuro (1998) and Thevanayagam (1998) established the effects of fines content and confining stress on liquefaction resistance. More recent works, (Akhila, Rangaswamy and Sankar, 2019a; 2019b; Swamy, Akhila and Sankar, 2021), have expanded on these findings, focusing on sand-kaolinite mixtures, where fines act as pore-fillers and modifiers of interparticle interactions. These mixtures exhibit unique mechanical responses due to the physicochemical properties of clay, which influence particle arrangement, permeability, and degradation of shear strength.

Initial studies primarily concentrated on monotonic behavior, exploring how fines content affects strength and compressibility. However, cyclic testing conditions revealed more interesting behaviors. For instance, increasing fines content initially reduces cyclic strength and dilatancy until a certain threshold, beyond which resistance begins to recover (Hyodo et al., 1994; Karim and Alam, 2014). Such non-linear trends suggest complex particle-level mechanics, especially at fines contents between 20% and 35%, where transition zones of fabric change are observed (Balreddy, Dinesh and Sitharam, 2021).

Findings by researchers like Benessalah, Arab and Meziane (2021) and Dafalla et al. (2020) confirm that even low-plasticity fines can significantly influence instability stress and shear modulus evolution. These studies align with observations by Wu et al. (2019), who highlighted creep and secondary compression effects in sand-clay systems. Additionally, Noorzad & Shakeri (2017) and Shan et al. (2022) demonstrated that low confining stresses worsen cyclic degradation, especially in high-fines specimens, affecting both ultimate and post-cyclic strengths.

Void ratio is essential for understanding the mechanical state of granular soils, making it a key parameter in this type of research. Traditional definitions of void ratio often fall short when applied to silty and clayey sands. Chang et al. (Chang, Wang and Ge, 2015; 2016) introduced refined models to better capture the minimum and maximum void ratios in such mixtures, providing a more precise framework for specimen reconstitution at targeted relative densities. These models consider the effects of fines content and particle packing mode, allowing for a more realistic depiction of the transitional behavior between sand-dominant and fines-dominant states. As a result, using these improved void ratio relationships ensures that the prepared specimens exhibit comparable fabric conditions across different fines contents, establishing a consistent basis for mechanical testing.

The recent work by Jagodnik and Sulovsky (2025) addressed the cyclic degradation of uniformly graded sands at small strains. Using strain-controlled cyclic triaxial tests on Drava River sand, they observed that initial hardening can occur before substantial pore water pressure build-up, contradicting older assumptions that degradation begins as soon as pore pressures rise. Their findings highlighted how relative density, effective confining stress, and frequency interactively govern the degradation index and pore pressure development, with low-strain hardening and high-strain softening defining the transition between stable and unstable responses. The results of this research were further expanded to sand-fine mixtures, with kaolinite as a fine component.

Despite advancements, the combined impact of fines and low confining stresses on the degradation index and pore water pressure development remains underexplored. This study aims to fill this gap by investigating the dynamic behavior of sand-kaolinite mixtures below the fines threshold under low confining stresses, focusing on stiffness degradation and pore pressure buildup. A series of undrained cyclic triaxial tests were performed using reconstituted specimens at constant relative densities, adjusted via void ratio modifications as outlined in earlier models by Chang et al. (Chang, Wang and Ge, 2015; 2016).

By combining results from sandy and sand-kaolinite mixtures, this research improves the understanding of how transitional soils behave under cyclic loads. The findings are essential for better liquefaction prediction and refining soil models.

2 METHODOLOGY

2.1 Materials Used

To investigate the cyclic behavior of soils under various confining stress levels, two types of uniform sand were tested (DROs018 and SK0), and sand-kaolinite mixtures containing 10% (SK10) and 15% (SK15) kaolinite by weight were prepared. Testing was performed at confining pressures of 25 kPa, 50 kPa, 100 kPa, and 200 kPa, representative of typical geotechnical field conditions. The sand was a clean, uniformly graded material with a specific gravity of 2.7 for SK0 sand and 2.66 for DrOS018 sand. The fine material used in this research was kaolinite, a commercially available clay with a specific gravity of 2.6, which was thoroughly dry-mixed with the sand to ensure homogeneity before specimen preparation for dynamic testing.

Key soil properties, including particle size distribution and Atterberg limits, were characterized using standardized procedures. Sieve analysis followed the European standard (ISO/TS 17892-4:2016, 2016), while the minimum and maximum void ratios (e_{min} and e_{max}) for the mixtures were estimated using analytical methods for binary soils as proposed by Chang, Wang & Ge (2015). The liquid and plastic limits of the pure kaolinite were determined following European standards (ISO/TS 17892-3:2015, 2015). However, for the sand-kaolinite mixtures, the fall cone method (ISO/TS 17892-6:2008, 2008) was adopted due to challenges in consistency limit determination. These challenges are further discussed in the study by Marušić & Jagodnik (2023; 2025). The results of the sieve analysis are presented in Figure 1. From Figure 1, it is evident that the two sand types are very similar.

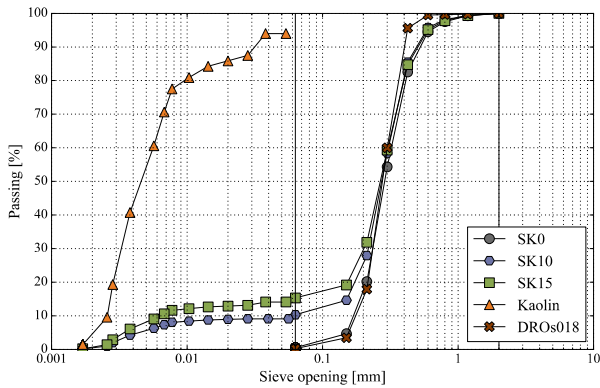


Figure 1. Sieve analysis of tested materials.

The physical properties of the tested materials are summarized in Table 1.

Table 1. Physical properties of materials used in research (Pajalić et al., 2021; Jagodnik & Arbanas, 2022; Marušić & Jagodnik, 2023, 2025; Jagodnik & Sulovsky, 2025)

Physical property	Material type				
	DR0S	SK0	SK10	SK15	SK100
Specific gravity, G_s (-)	2.66	2.7	2.69	2.67	2.6
Eff. Particle size, D_{10} (mm)	0.18	0.183	0.054	0.0045	0.00258
Minimum void ratio, e_{min} (-)	0.627	0.641	0.473	0.390	0.850
Maximum void ratio, e_{max} (-)	0.951	0.911	0.716	0.619	1.640
Plastic limit, w_{PL} (%)	N/A	N/A	N/A	N/A	21.6
Liquid limit, w_{LL} (%)	N/A	N/A	N/A	N/A	48.3

2.2 Sample Preparation

The specimens were prepared with varying kaolinite content, adjusting the proportion of kaolinite clay to study its effect on soil behavior. Samples were prepared using a well-established undercompaction method developed by Ladd (1978) with 5% of undercompaction. This method ensured that samples had a continuous density throughout the height of the specimen. Despite the drawbacks of the undercompaction method, the method is widely used for these types of soil mixtures and much more (Tatsuoka, Muramatsu & Sasaki, 1982; Amini & Qi, 2000; Polito & Ii, 2001; Xiao et al., 2019; Porcino et al., 2021; Reid & Fanni, 2022; Li, Russell & Muir Wood, 2024; Pokhrel et al., 2024).

All the samples with kaolinite powder were prepared according to the method proposed by Chang, Wang and Ge, (2015). The results presented in this paper are for the samples prepared at the initial relative density of 80%. The initial void ratio of the specimens prior to saturation is presented in Table 2.

Table 2. Initial void ratio values of tested materials

Specimen type	Initial void ratio
DrOS018	0.692
SK00	0.695
SK10	0.529
SK15	0.446

2.3 Testing equipment

The tests were performed using a computer-controlled cyclic triaxial testing system. Throughout the tests, axial load, axial displacement, and pore water pressure were constantly monitored and recorded with electronic transducers and data acquisition systems. The system used in this study is well-detailed in the papers written by the authors (Jagodnik and Sulovsky, 2025; Jagodnik et al., 2025). Special attention was given to PID control settings because of the sensitivity of the closed-loop computer system.

2.4 Testing Procedure

Before cyclic loading, the samples were saturated using a back-pressure saturation technique to ensure full saturation, as required for undrained testing. Back pressurizing was performed in steps to avoid overconsolidation during saturation (Lade, 2016). The increment of stress for low confining tests was 30 kPa, while for higher confining stresses, 50 kPa stress increment was applied. This resulted in a B value of 0.99 on average.

During the cyclic triaxial tests, the samples were subjected to sinusoidal loading at a constant frequency. The frequency of 0.1 Hz was selected to simulate seismic cyclic loading, as suggested by studies on dynamic soil behavior (Jagodnik & Sulovsky, 2025), as shown in Table 3. Specimen loading was applied in steps, after which the specimen was reconsolidated before the following loading cycle.

Table 3. Initial loading parameters of the tested materials

System type	Loading type	Loading values
Dynamic triaxial test	Cyclic axial strain [%]	0.005, 0.0067, 0.013, 0.033, 0.05, 0.067, 0.13

3 RESULTS & DISCUSSION

This section presents the results of the cyclic triaxial tests performed on pure sand and sand–kaolinite mixtures with two different kaolinite contents and confining stresses. Key observations focus on the progression of the degradation index and excess pore water pressure, emphasizing the impact of kaolinite fines and strain amplitude on the dynamic response of the mixtures.

Stiffness degradation for strain-controlled tests is calculated as suggested by Mortezaie & Vucetic (2016), Vucetic, Thangavel & Mortezaie (2021), and Jagodnik and Sulovsky (2025), and defined with Equation (1).

$$\delta = \frac{G_{s,av,N}}{G_{s,av,1}} \quad (1)$$

where: $G_{s,av,N}$ is the average secant shear modulus of the N-th cycle, and $G_{s,av,1}$ is the average secant shear modulus of the first cycle.

The normalized pore water pressure ratio is calculated using Equation (2).

$$r_u = \frac{\Delta u}{\sigma'_c} \quad (2)$$

where: Δu is the change of the pore water pressure, and σ'_c is the effective confining pressure of the test.

The typical results of how the stiffness degradation index changes with cycles and its relation to the normalized pore water pressure are shown in Figures 2 and 3.

Figure 2 presents the evolution of the stiffness degradation index (δ) with the number of loading cycles (N) for sand–kaolinite mixtures subjected to small cyclic shear strains of 0.01% (Figure 2(a)), 0.05% (Figure 2(b)), and 0.1% (Figure 2(c)). At the smallest strain amplitude ($\gamma_c=0.01\%$), all mixtures, regardless of kaolinite content or confining stress, exhibited minimal degradation, with δ values remaining close to or slightly above the value of 1. As the strain amplitude increased to 0.05%, a gradual decrease in stiffness became clear, while mixtures with 10% and 15% kaolinite (SK10 and SK15) showed more stable behavior, indicating that the presence of fines delayed the start of degradation.

At the highest tested strain amplitude ($\gamma_c=0.1\%$) degradation became more pronounced across all samples. The SK 00 specimens, especially under low confining stress ($\sigma'_c=25$ kPa), experienced rapid stiffness loss. In contrast, the SK15 mixtures showed comparatively better resistance, maintaining δ values closer to 1 for several cycles. These results highlight two main trends: increasing confining stress reduces degradation, and adding a moderate amount of kaolinite fines (up to 15%) can enhance the cyclic stability of the mixture under small to moderate strain conditions. The influence of kaolinite fines seems particularly beneficial at strain levels where clean sands start to degrade, supporting earlier findings that fines can improve interparticle bonding and fabric stability during cyclic loading.

The relationship between stiffness degradation (δ) and normalized pore water pressure (r_u) for sand–kaolinite mixtures is illustrated in Figure 3, for cyclic shear strain amplitudes of 0.01% (Figure 3(a)), 0.05% (Figure 3(b)), and 0.1% (Figure 3(c)). At the lowest strain level (Figure 3(a)), all samples cluster around $\delta \approx 1$, with (r_u) remaining well below the conventional liquefaction threshold ($r_u=0.65$), indicating that negligible

degradation occurs in this strain regime. Increasing the confining stress from 25 kPa to 50 kPa slightly enhances stiffness retention, especially in mixtures with kaolinite (SK10 and SK15). The data generally stays within or above the degradation envelope of the reference Drava sand (DrOS018), indicating better cyclic resilience with the addition of kaolinite fines.

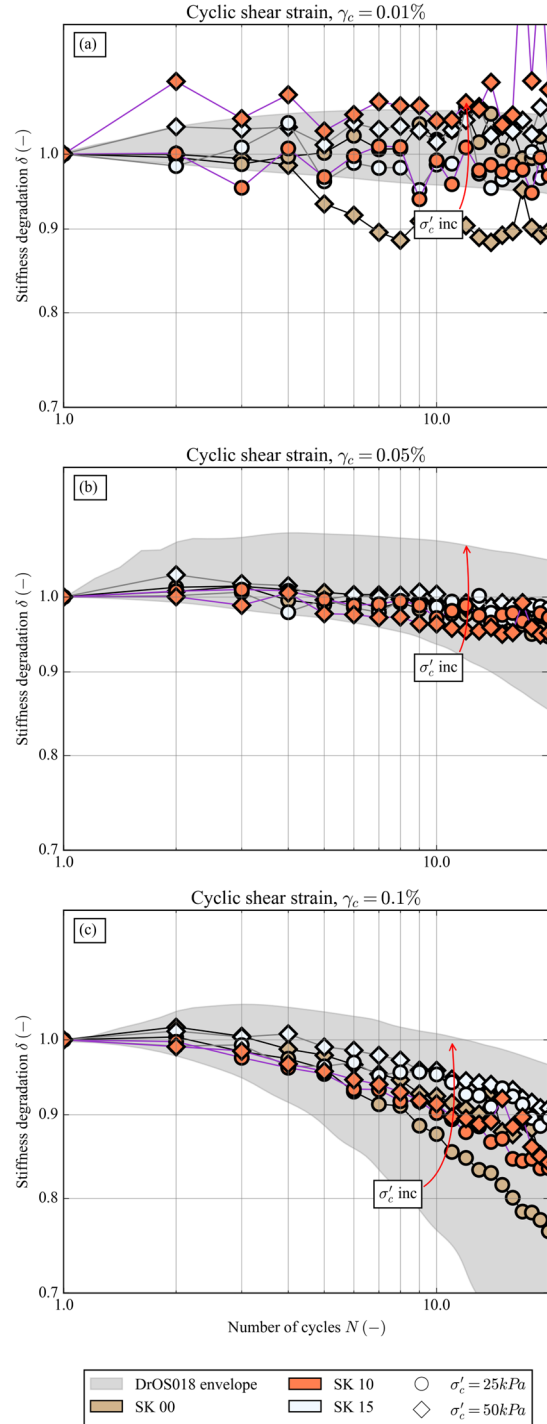


Figure 2. The change of stiffness degradation index with number of cycles: (a) cyclic shear strain 0.01%, (b) cyclic shear strain 0.05% and (c) cyclic shear strain 0.1%.

At $\gamma_c=0.05\%$ (Figure 3(b)), a similar trend is seen, but a clearer difference appears among mixtures. Samples without fines (SK00) show a more noticeable decrease in δ compared to

those with fines, confirming that adding kaolinite helps preserve structural stability under increasing pore pressures. The response still mainly stays within the limits of the DrOS018 envelope, reinforcing that at this moderate strain level, both kaolinite content and confining stress help reduce pore pressure-related degradation.

In contrast, at $\gamma_c=0.1\%$ (Figure 3(c)), degradation becomes more significant and systematically correlates with increasing (r_u). Samples approach or surpass the $r_u = 0.65$ threshold, where liquefaction potential turns critical. The SK 00 mixtures exhibit the most severe degradation, with δ values dropping below 0.8 in some cases, while SK 15 mixtures perform noticeably better, especially under higher confining stress. These findings confirm that kaolinite fines improve cyclic stability by delaying pore pressure buildup and maintaining stiffness. Additionally, the divergence from the Drava sand envelope at this strain level highlights the complex interaction between pore pressure generation and material degradation in sand–clay systems.

To further investigate the link between pore pressure development and stiffness loss, Figure 4 illustrates how the stiffness degradation index (δ) changes with the number of loading cycles (N) for three levels of cyclic shear strain: 0.01% (Figure 4(a)), 0.05% (Figure 4(b)), and 0.1% (Figure 4(c)). These plots show how degradation builds up over time, especially under different kaolinite contents and confining stress conditions. At the lowest strain amplitude ($\gamma_c=0.01\%$, Figure 4(a)), the degradation index remains low and stable, mostly between 0.03 and 0.10, regardless of content. The influence of confining pressure becomes more evident at higher cycles, with higher σ'_c generally associated with slightly higher δ , indicating minor cumulative degradation.

At the intermediate strain level ($\gamma_c=0.05\%$, Figure 4(b)), a more apparent divergence becomes evident. The clean sand mixtures (SK00) show the most substantial increase in δ , especially under higher confining stress, where δ reaches approximately 0.30 by the 20th cycle. Conversely, kaolinite-containing mixtures (SK10 and SK15) consistently display more gradual degradation patterns and largely stay within the shaded envelope representing the performance of the reference Drava sand (DrOS018). This indicates that kaolinite fines improve cyclic stability by slowing down the rate of stiffness loss over cycles.

As expected, degradation trends become more pronounced at the highest strain amplitude ($\gamma_c=0.1\%$, Figure 4(c)), with all mixtures showing a steady increase in δ as the number of cycles rises. However, the stabilizing effect of kaolinite remains clear; SK10 and SK15 mixtures keep δ values below 0.40, while clean sands go beyond that range. These results emphasize that kaolinite fines represent an important factor in stiffness degradation under repeated cyclic loading.

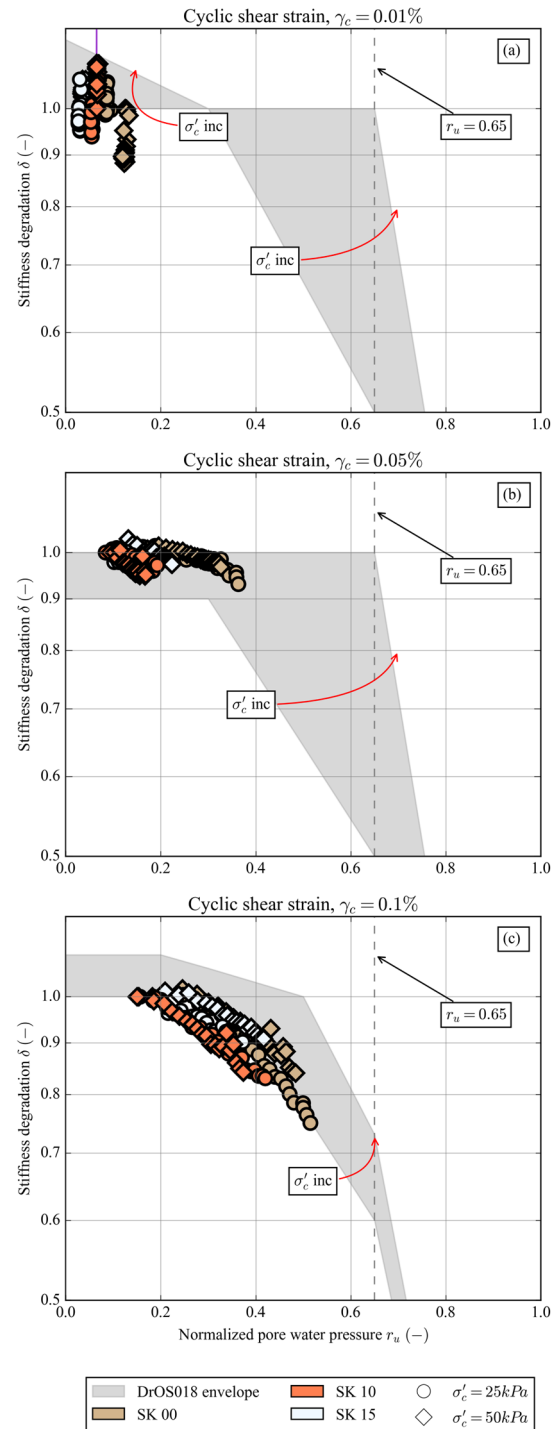


Figure 3. The change of stiffness degradation index with normalized pore water pressure ratio: (a) cyclic shear strain 0.01%, (b) cyclic shear strain 0.05% and (c) cyclic shear strain 0.1%.

4 CONCLUSIONS

The results of this study clearly show that both kaolinite fines content and effective confining stress significantly affect the cyclic stiffness degradation behavior of sand-kaolinite mixtures. Within the tested range of fines contents (0-15%) and confining stresses (25-50 kPa), the presence of kaolinite consistently improved cyclic stability, especially under small to moderate strain amplitudes ($\gamma_c = 0.01-0.1\%$). At the lowest strain level, all mixtures maintained nearly constant stiffness, while at higher strain amplitudes, the clean sand (SK 00) experienced accelerated degradation and earlier pore pressure buildup. In contrast, mixtures with 10% and 15% kaolinite (SK 10 and SK 15) retained higher stiffness over more cycles. They exhibited delayed degradation onset, indicating that a moderate amount of kaolinite can have a stabilizing effect on cyclic response.

The beneficial role of kaolinite can be attributed to improved interparticle bonding and contact stability between sand grains. The kaolinite fills void spaces and creates more contact points, distributing stresses more evenly and reducing local strain concentrations that can cause stiffness loss. Higher confining stress further enhances the cyclic response, indicating that denser contact networks and lower void ratios help prevent stiffness degradation and delay excess pore pressure buildup. The link between the stiffness degradation index (δ) and the normalized pore pressure ratio (r_u) confirms that pore pressure accumulation is a reliable sign of stiffness deterioration under cyclic loading.

This work examined mixtures with kaolinite as the fine fraction, but the mechanisms, such as improved force-chain stability, reduced pore pressure, and delayed degradation, likely can be related to other fine-grained material with similar plasticity and surface activity.

The study shows that adding a moderate amount of clay-sized fines like kaolinite improves the cyclic resistance of sand-fines mixtures by stabilizing soil fabric and reducing stiffness loss. These findings provide a solid basis for understanding how kaolinite affects sand's micromechanical behavior under cyclic loading. Future research with advanced imaging and DEM simulations could clarify contact network and pore structure evolution, enabling better predictions of cyclic performance in geotechnical uses.

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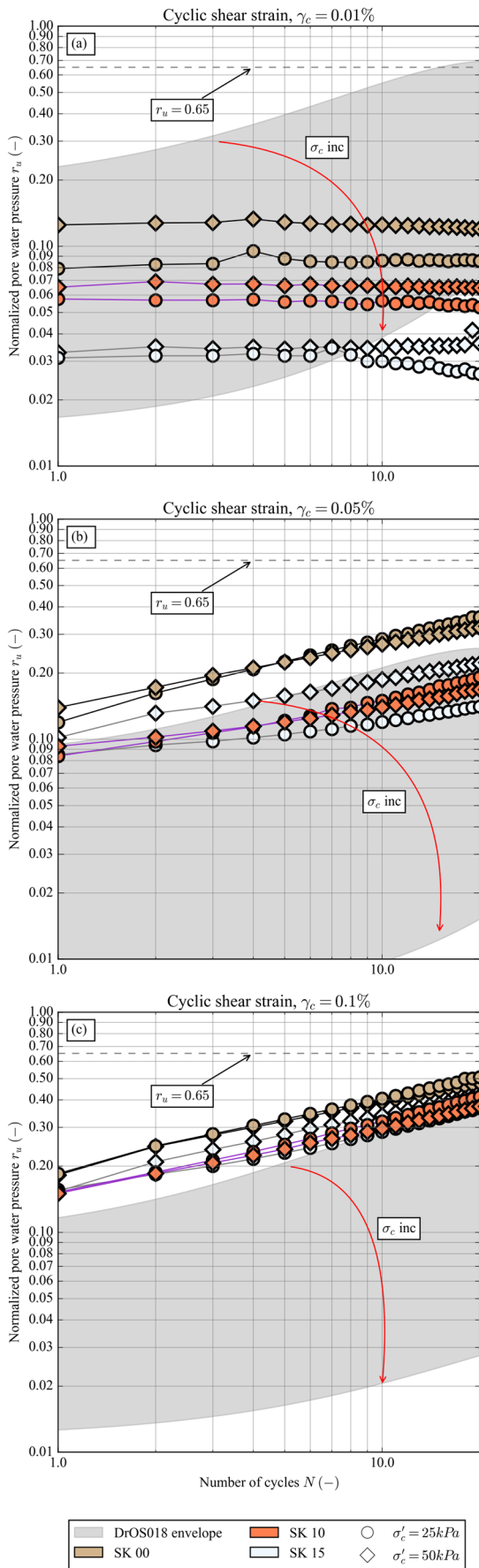


Figure 4. The change of normalized pore water pressure with number of cycles: (a) cyclic shear strain 0.01%, (b) cyclic shear strain 0.05% and (c) cyclic shear strain 0.1%.

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