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The effect of sand grading on cyclic resistance under direct simple shear.

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ABSTRACT: The cyclic resistance of sand is a critical characteristic for assessing the long-term performance of offshore foundations. In the field, the load-bearing capacity of a foundation can be weakened by cyclic loading from the environment, due to increases in excess pore water pressure and changes in particle arrangement. Previous studies have shown that the grading of sand can significantly influence soil behavior, including permeability, friction angle, dilation angle, and liquefaction resistance. However, there remains a lack of comprehensive research on how grading affects cyclic resistance under cyclic direct simple shear (CDSS) conditions, where shear stress is the primary focus. In this study, four uncrushable sand samples with distinct gradings were tested under constant-volume conditions and subjected to varying levels of cyclic shear stress. The investigation focused on their stress-strain responses, excess pore pressure evolution, and cyclic degradation behavior. These samples had different coefficients of uniformity (C_u), ranging from well-graded to poorly graded, with particle size distributions conforming to fractal characteristics. Furthermore, the study quantified the influence of grading on the variability of CDSS results. The results show that increasing C_u transforms cyclic response from loose-like to dense-like, delays pore pressure accumulation, and improves cyclic resistance, although the enhancement levels off when C_u exceeds approximately 3.1. The variability of test results increases with C_u up to 3.1 and decreases slightly thereafter. These findings provide valuable insights into the dynamic properties of sands with varying gradings under direct simple shear conditions and practical guidance for estimating cyclic resistance in offshore foundation design.

KEYWORDS: sand grading, cyclic direct simple shear, constant volume, coefficient of uniformity

1 INTRODUCTION

Offshore foundations, such as monopile and gravity base, are frequently subjected to dynamic environmental loading from waves, currents, and storms (Andersen, 2015). These cyclic loads are typically of small magnitude but vary rapidly over short time scales. Under repeated loading, the surrounding seabed sediments may accumulate excess pore water pressure, leading to stiffness degradation (Seed and Idriss, 1971). Simultaneously, particle rearrangement and changes in the contact network can occur, which in loose sand may trigger a loss of strength, while in dense sand may result in cyclic strain mobility. All these phenomena can significantly reduce the bearing capacity and degrade the long-term performance of offshore foundations. To evaluate these effects, laboratory testing methods such as the cyclic triaxial (CTX) test and cyclic direct simple shear (CDSS) test are commonly used. The CDSS apparatus applies a controlled cyclic shear stress directly to the horizontal plane of the specimen, better simulating the in-situ simple shear stress state of seabed soils compared with the CTX test. Moreover, the constant-volume control in CDSS (equivalent to the undrained conditions in CTX) allows for indirect estimation of excess pore pressure development and enables higher testing efficiency (Dyvik et al., 1987).

Sand grading is a key factor governing its mechanical response, as variations in particle size distribution influence fundamental properties such as permeability, internal friction angle, dilation angle, and resistance to liquefaction (Yang and Sze, 2011; Belkhatir et al., 2012; Doygun, Brandes and Roy, 2019). Changes in grading modify the void ratio, force-chain network, and particle contact conditions, thereby altering cyclic loading behavior. Well-graded sands generally exhibit enhanced cyclic resistance due to improved interlocking and void filling by finer particles (Yang and Sze, 2011). However, the specific role of grading parameters remains debated. For example, Doygun et al. (2019) conducted CDSS tests on sands with different gradings and fines contents to investigate their effects. The results indicated that cyclic strength decreased with increasing C_u and decreasing d_{50} when the fines content approached 50%. Similarly, Vaid et al. (1990) used CTX tests to investigate the relationship between grading and liquefaction resistance, and found that, at a higher relative density of 70%, increasing C_u while maintaining d_{50} reduced liquefaction resistance. In contrast, Yilmaz et al. (2008) presented an opposing view, based on a series of binary sand grading (mixture of fines and coarse particles) tests and reported no consistent correlation between C_u and cyclic resistance. These contrasting results suggest that the influence of grading is not universal and may depend on factors such as relative density, fines content and testing method.

However, most previous studies have examined binary mixtures or discrete gradation types, often based on a limited number of samples. Such approaches may not fully reflect the influence of higher C_u values and the resulting non-uniform particle arrangements. Continuous gradings, which are common in natural seabed deposits, have received comparatively little attention. In addition, most grading-related liquefaction studies have been conducted using cyclic triaxial tests, with relatively few performed under constant-volume CDSS conditions, which more closely represent the in-situ simple shear stress state.

In this study, four artificial gradings with fractal particle size distributions were prepared from uncrushable quartz sands. CDSS tests at multiple CSR levels were conducted on specimens of the same relative density to investigate the influence of C_u on cyclic resistance. The results show that increasing C_u produces dense-like cyclic behavior, delays pore pressure buildup, and enhances cyclic resistance, with the improvement plateauing beyond C_u = 3.1. The variability of test results increases with C_u up to 3.1 and then sightly decreases, providing new insights into the uncertainty of cyclic resistance evaluation using CDSS tests.

2 MATERIAL AND METHODS

The sand material used in this study is a commercially produced quartz sand as the main sand. To compensate for the lack of fine particles in the main sand, another type of sand with relatively finer quartz particles was added to adjust the particle size distribution (PSD). Both sands have similar mineralogical compositions and are considered uncrushable under the stress levels applied in this study.

The influence of particle grading was examined by preparing four artificial gradings and performing cyclic direct simple shear tests under constant-volume conditions. The gradings were designed using particle fractal theory, which was originally developed and applied in geotechnics to describe particle breakage processes and the evolution of PSD under multiple energy inputs. Natural sands, formed through rock weathering and crushing, often exhibit PSDs that follow a fractal distribution. According to Equation (1), the artificial gradings were generated by varying the fractal dimension α. Where the d_M is the maximum particle diameter (Xiao et al., 2021). The corresponding PSD curves and particle images are shown in Figures 1(a) and 1(c). As α decreases, the coefficient of uniformity (C_u) also increases (from 1.1 to 6.0), indicating a broader particle size range. In samples with higher C_u, fine particles can fill the voids between coarse particles, leading to smaller extreme void ratios (e_{min} and e_{max}), as illustrated in Figure 1(b).

$$F(d) = \left(\frac{d}{d_M}\right)^{3-\alpha} \tag{1}$$

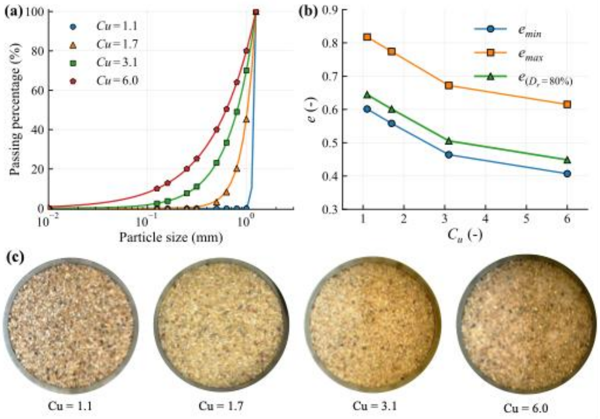

Figure 1. (a) Particle size distribution curves; (b) extreme void ratio and sample void ratio; (c) Photographs of prepared samples.

All samples were consolidated to a relative density of approximately 80% under a vertical stress of 200 kPa, representing typical dense sediment conditions surrounding offshore foundations. For each grading, multiple cyclic shear stress levels were applied to evaluate cyclic response and resistance. All CDSS tests were conducted on dry specimens to improve operational efficiency and comply with ASTM standards (ASTM, 2019). In constant-volume CDSS tests, excess pore pressure was inferred from the reduction in vertical stress. The apparatus applied a sinusoidal cyclic shear stress to the specimen, with the bottom platen moving laterally to both sides, and all test data were recorded automatically. An active constant-volume control mode was used, in which the control system adjusted the vertical position of the top cap to maintain a constant vertical LVDT reading, thereby minimizing the influence of device frame deformation. All tests were performed under stress-controlled conditions at a loading frequency of 0.1 Hz.

3 RESULT AND DISCUSSION

3.1 *Stress-Strain response*

Figure 2 presents the cyclic shear stress-strain relationships for four gradings under the same cyclic stress ratio (CSR = 0.10). From (a) to (d), the coefficient of uniformity C_u increases from 1.1 to 6.0. Although all specimens were prepared at the same relative density, their cyclic responses vary significantly. For the C_u = 1.1 sample, the hysteresis loops expand rapidly within the first few cycles, a behavior typically observed in relatively loose sands. In contrast, for the C_u = 6.0 sample, the loops remain compact for a prolonged number of cycles, indicating slower strain accumulation. Two characteristic cycles are highlighted: the orange-marked cycle (N_e) corresponds to the threshold shear strain of 0.75%, which separates the linear-like response stage from the strain accumulation stage; the green-marked cycle (N_f) corresponds to the assumed failure shear strain of 5%. As C_u increases, both N_e and N_f increase, with the C_u = 1.1 sample showing notably smaller values than the others. The difference between N_e and N_f reflects the number of cycles sustained in the strain accumulation stage, which becomes longer for higher C_u specimens. This trend indicates a shift in cyclic behavior from a loose-like response to a dense-like response with increasing C_u. At the large-strain accumulation stage, the hysteresis loops for all samples show a similar pattern: near the origin, displacement increases rapidly under low stress levels, whereas at larger strains, the samples regain strength. This strength recovery is attributed to particle rearrangement and is analogous to sand dilation.

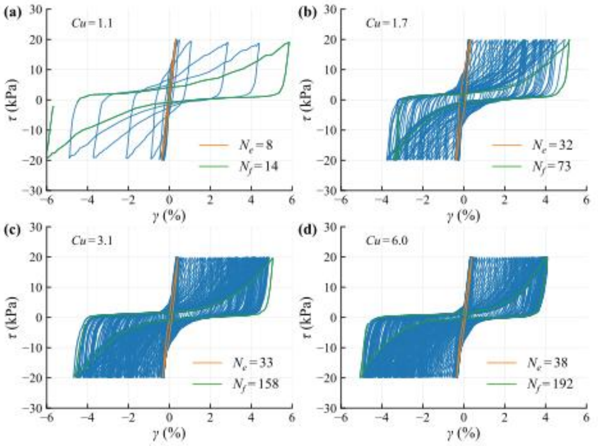

Figure 2. Stress-strain response for samples with (a) C_u = 1.1; (b) C_u = 1.7; (c) C_u = 3.1; and (d) C_u = 6.0.

Figure 3 shows the evolution of maximum shear strain per cycle with the number of cycles for two CSR levels (0.10 and 0.12). At both cyclic stress amplitudes, higher C_u specimens require more cycles to reach the same strain. The cyclic resistance increases markedly from C_u = 1.1 to C_u = 3.1, while the difference between C_u = 3.1 and C_u = 6.0 is relatively small, consistent with the trends observed in Figure 2. For lower C_u specimens, strain develops rapidly with little or no initial plateau, whereas higher C_u specimens often exhibit a short initial stable phase before strain begins to accumulate more gradually. This initial plateau is more evident at the lower stress ratio (CSR = 0.10), reflecting enhanced stability in well-graded sands under small cyclic loads.

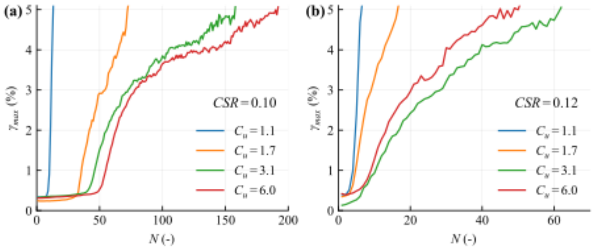

Figure 3. Evolution of maximum shear strain with number of cycles under (a) CSR = 0.10; (b) CSR = 0.12

3.2 *Excess pore pressure evolution*

In constant-volume CDSS tests, excess pore pressure was not directly measured but inferred from the reduction in vertical stress from the initial vertical stress. In saturated specimens, this reduction in vertical stress is fully carried by the pore water.

Figure 4 presents the evolution of vertical stress alongside cyclic shear stress for specimens with C_u values of 1.1, 1.7, 3.1, and 6.0 under CSR = 0.10. The vertical stress degradation process can be divided into three stages: (1) a rapid initial drop occurring within the first few cycles, indicating the onset of contractive behavior; (2) a gradual and stable reduction where the rate of stress decrease is slow, corresponding to a steady accumulation of pore pressure under constant-volume conditions; and (3) a full liquefaction stage characterized by the vertical stress approaching zero.

Comparing the four gradings shows that specimens with higher C_u delay the onset of rapid pore pressure buildup, as indicated by the greater number of dense hysteresis loops before reaching liquefaction. Two characteristic cycles are defined: N_h, corresponding to a pore pressure ratio of 50% (half liquefaction), and N_p, corresponding to a pore pressure ratio of 98% (full liquefaction). For example, N_h and N_p increase from 8 and 14 cycles for C_u = 1.1 to 25 and 67 cycles for C_u = 6.0, respectively, indicating that increasing C_u enhances resistance to pore pressure development. Notably, N_f is typically greater than N_p, suggesting that liquefaction, defined by pore pressure ratio threshold, occurs before the complete loss of cyclic resistance in the sample.

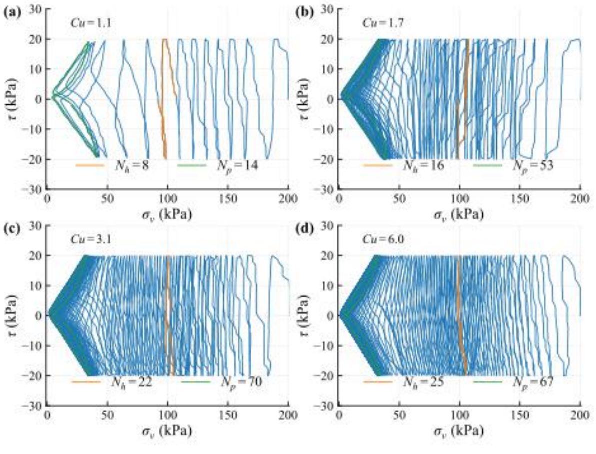

Figure 4. Evolution of vertical stress for samples with (a) C_u = 1.1; (b) C_u = 1.7; (c) C_u = 3.1; and (d) C_u = 6.0.

Figure 5 shows the normalized excess pore pressure ratio (r_p) versus the number of cycles for two CSR levels (0.10 and 0.12). At CSR = 0.10, three distinct stages of pore pressure development can be clearly distinguished. In contrast, at CSR = 0.12, the development becomes more continuous and steeper, without a distinct slow developing phase, as the higher cyclic stress accelerates pore pressure generation. Overall, increasing C_u slows the r_p buildup under both stress levels, indicating improved liquefaction resistance. This improvement can be attributed to the ability of finer particles to occupy voids between coarser particles, reducing the available space for particle rearrangement and enhancing the stability of the soil skeleton under cyclic loading.

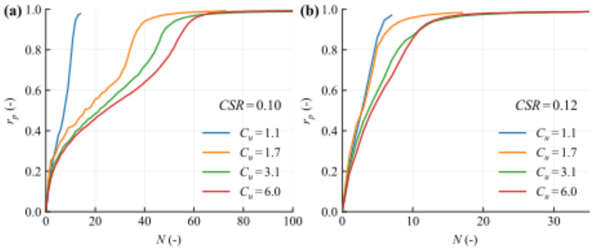

Figure 5. Evolution of pore pressure ratio with number of cycles under (a) CSR = 0.10; (b) CSR = 0.12

3.3 S-N degradation curves and uncertainty

The four sand gradings were tested in the CDSS apparatus under multiple cyclic stress ratios, and the relationship between the number of cycles to failure (N_f) and CSR is presented as S-N degradation curves in Figure 6 (a). The regression model given in Equation (2) was used to fit the data, where a and b are fitting parameters. The results clearly show that the C_u = 1.1 sample lies consistently at the bottom of the curve set, indicating that uniform sand exhibits the weakest cyclic resistance. Increasing C_u to 1.7 results in a marked improvement in resistance, consistent with earlier observations from stress-strain and pore pressure responses. However, further increasing C_u to 3.1 and 6.0 leads to a plateau in cyclic resistance, suggesting that beyond a certain grading threshold, additional increases in particle size range offer limited benefit to cyclic strength.

$$CSR = a \times lg\left(N_f\right)^b \tag{2}$$

In addition to the mean resistance trend, the results highlight the inherent variability in CDSS testing. This variability can be visualized in Figure 6(b) as the scatter of data points. For the C_u = 1.1 group, the points are closely clustered around the fitting line, indicating higher repeatability and lower variability. As C_u increases, the spread of points becomes larger, reflecting increased variability in the measured N_f values. This may result from more complex load transfer paths and particle rearrangements in well-graded sands, which can lead to localized differences in cyclic response between specimens.

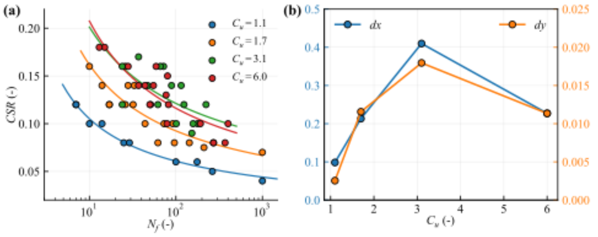

Figure 6. (a) S-N degradation curves; (b) variation of uncertainty for different C_u.

$$dx = \frac{1}{n}\sum_{i=1}^{n}\left|\log_{10}\left(\frac{N_f}{f(\mathrm{CSR})}\right)\right| \tag{3}$$

$$dy = \frac{1}{n}\sum_{i=1}^{n}\left|\mathrm{CSR} - f^{-1}\left(N_f\right)\right| \tag{4}$$

The degree of variability was quantified using the variation index, as shown in Equation (3)-(4) (Sun, Stuyts and Haegeman, 2025), and the results are shown in Figure 6 (b). The variation index increases with C_u from 1.1 to 3.1, peaking at C_u= 3.1, and then decreases slightly at C_u = 6.0. Both cyclic number (dx) and CSR (dy) exhibit the same trend. This trend suggests that intermediate gradings may produce the most heterogeneous particle arrangements, while very high C_u mixtures achieve a more stable packing structure due to more effective void filling by fines, thereby reducing variability.

4 CONCLUSIONS

Cyclic direct simple shear tests were conducted on four sand gradings with different coefficients of uniformity (C_u) and the same relative density. The main conclusions are:

(1) Increasing C_u alters the cyclic stress–strain behavior from loose-like to dense-like, leading to slower strain accumulation and delayed pore pressure buildup. Higher C_u

specimens show greater cyclic resistance. Moreover, liquefaction, defined by excess pore pressure ratio, often occurs before complete loss of cyclic resistance for the higher C_u samples.

(2) The S–N degradation curves indicate that the sample with C_u = 1.1 has the weakest cyclic resistance, which increases markedly at C_u= 1.7 and reaches a plateau beyond C_u = 3.1, suggesting a grading threshold beyond which further improvement may be limited.

(3) The results for uniform specimens show a small range of fluctuation. The variability of results increases with C_u up to 3.1, reflecting more complex particle packing and load transfer paths. Then, it decreases slightly at C_u = 6.0, possibly due to a more stable interparticle structure.

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