Effect of Static Shear Stress on Cyclic Resistance of a Uniform Gravel

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ABSTRACT

Sloping ground conditions, such as those found in dams and levees, as well as buildings, result in an initial horizontal static shear stress in the ground, affecting its cyclic resistance. When liquefaction triggering is a concern, the K_α correction factor is used to account for this initial static stress in a simplified manner. Laboratory testing was performed to assess the effects of horizontal static shear stress on saturated sands; however, limited data exists for this effect on gravels. In this study, cyclic direct simple shear tests were performed on a uniform gravel to determine the effects of relative density, confining stress, and pore pressure generation on cyclic resistance at increasing values of initial horizontal static shear stress. Tests were conducted using a large-size cyclic direct simple shear (CDSS) device in constant volume conditions on 9mm D_{50} specimens of a pea gravel (PG9). The effects of relative density on the cyclic resistance of this material were analyzed for loose (47%) and dense (87%) specimens, at three significant vertical effective stresses: 100, 250, and 500 kPa. Testing results show that an increasing horizontal static shear stress has a significant effect on the cyclic resistance and pore pressure generation of both dense and loose uniform gravels, but is more pronounced for loose uniform gravels.

INTRODUCTION

Sloping ground conditions, such as those encountered in dams, levees, and many infrastructure projects, cause horizontal static shear stress to the soil, greatly affecting its response to cyclic loading. This initial static shear stress is compounded by the cyclic shear component caused by the earthquake loading (Boulanger and Seed, 1995). While many of these sites are composed of gravelly soils, the nature of gravelly soils in sloping conditions is not well investigated.

Because the stress-state is different between level ground and sloping ground, Seed (1983) developed a procedure to correct for ground conditions where static pre-shearing is present. This K_α correction factor correlates level ground conditions to sloping ground conditions. K_α is the ratio of cyclic strength at liquefaction in sloping ground conditions to the cyclic strength in level ground conditions and is given by

$$K_\alpha = \frac{\dfrac{\tau_{c,\alpha}}{\sigma'_{v0}} - \alpha}{\dfrac{\tau_{c,\alpha=0}}{\sigma'_{v0}}} \qquad [1]$$

where $\tau_{c,\alpha} / \sigma'_{v0}$ is the normalized shear stress at liquefaction in sloping ground conditions and $\tau_{c,\alpha=0} / \sigma'_{v0}$ is the normalized shear stress at liquefaction in level ground conditions. Alpha, α, is the ratio of initial static shear stress to initial vertical effective stress, and is 0 for level ground conditions.

Data is available on the cyclic behavior of sands with static pre-shearing. Vaid and Chern (1985) performed cyclic triaxial tests on dense tailings sands and concluded that higher confining stresses make soils more contractive and thus decrease the K_α correction factor. Seed and Harder (1990) performed cyclic triaxial tests for vertical confining stresses less than about 300 kPa. They found that K_α decreases for loose specimens and increases with increasing α for dense specimens. Seed and Harder (1990) also concluded that K_α will decrease for contractive soils at higher vertical stresses. Boulanger and Seed (1995) performed tests on reconstituted specimens of sub-angular Sacramento River sand using a direct simple shear apparatus, for a range of loose to medium dense states. Sivathayalan and Ha (2011) performed both direct simple shear and cyclic triaxial tests on subrounded and semi-angular sands and concluded that the cyclic response of soils under initial static stress depends on density and confining stress as well as the type of loading and material fabric.

In comparison to sands, very little testing has been performed for gravelly soils. Haeri et al. (2018) conducted a series of cyclic triaxial tests on a rounded gravelly soil and found that increases in the static shear stress increase the cyclic resistance ratio under low confining pressure and decrease the pore pressure generated at failure. Of the tests performed on gravels, even less data is available in cyclic simple shear (Seyed Ghafouri, 2018; Haeri et al., 2018), particularly due to the size limitations of the conventional simple shear device.

For this study, K_α testing was performed using a large-size cyclic direct simple shear device to assess the effects of horizontal static shear stress on the undrained cyclic behavior of a uniform gravel. The results of these tests are used to evaluate the effects of relative density, vertical confining stress, and pore pressure generation on cyclic resistance at increasing values of initial horizontal static shear stress.

TEST EQUIPMENT AND MATERIALS

Cyclic tests were performed using a prototype large-size cyclic direct simple shear (CDSS) device. The device allows for testing of large-size particles, such as gravels, by utilizing stacked shear rings, each with internal diameter of 307 mm and maximum specimen height of 137 mm. A description of the device can be found in Zekkos et al. (2018). It has been shown that cyclic direct simple shear loading more closely simulates the rotation of principal stresses experienced in situ during shaking compared to cyclic triaxial loading and thus cyclic direct simple shear is a more realistic representation of soil behavior under earthquake loading (Boulanger, 2003; Sivathayalan and Ha, 2011; Cappellaro et al., 2018; Mohtar et al., 2018).

Specimens were composed of a uniform sub-rounded pea gravel with a 9 mm D_{50} (PG9). Shear wave velocity (V_s) measurements were conducted prior to each cyclic direct simple shear test using Micro-Electro-Mechanical Systems (MEMS) type accelerometers placed at the baseplate and top cap of the device. Each accelerometer measures acceleration with a range of ± 1.7g and a sensitivity of 1000 mV/g, and allows for low-noise interpretation of wave arrival from the bottom of the specimen to the top of the specimen. Horizontally polarized, vertically propagating shear waves were generated by striking the base plate with a rubber mallet and allowing the impulse to travel through the specimen to the top plate.

TEST PROCEDURE

Specimens of PG9 were prepared as detailed in Hubler (2017) and Hubler et al. (2017). Each specimen was prepared via dry deposition with a diameter of 307 mm and a height of 112 mm. Two target relative densities were used for testing: loose (Dr = 47%) and dense (Dr = 87%), as determined using ASTM C29 (ASTM, 2010). Loose specimens were prepared at a relative density of 47% ± 4% by placing the gravel with a small shovel and a zero drop height. Dense specimens were prepared at 87% ± 4% relative density in 5 layers, first by dry depositing the gravel with a small shovel, then by tamping with a 5 kg weight with diameter of 150 mm from a height of 50 mm a total of 25 times per layer.

Testing was performed in three stages: (1) vertical load application and "consolidation" in K_0 conditions, (2) horizontal constant load monotonic shearing to target stress level, and (3) constant-volume, stress-controlled horizontal shearing. Consolidation to K_0 conditions was achieved through staged loading to a target vertical stress of 100 kPa, 250 kPa, or 500 kPa. The 1 atm pressure (~100 kPa) was used as a baseline and corresponds to ~5 m depth for a typical profile. The 500 kPa vertical stress series was selected to represent field conditions with high overburden stress either due to large depth (~25 m), or larger overlying structures such as dams.

Static shear stress ratios, or α values, of 0, 0.05, 0.1, and 0.2 were reached through horizontal monotonic shearing. While other studies on sands and silts have reached α values as high as 0.3 (Boulanger and Seed, 1995; Sivathayalan and Ha, 2011), PG9 was tested up to horizontal static shear stress ratios of 0.2. This is because many specimens at $\alpha = 0.2$ only withstood a single loading cycle before reaching liquefaction, particularly for loose specimens.

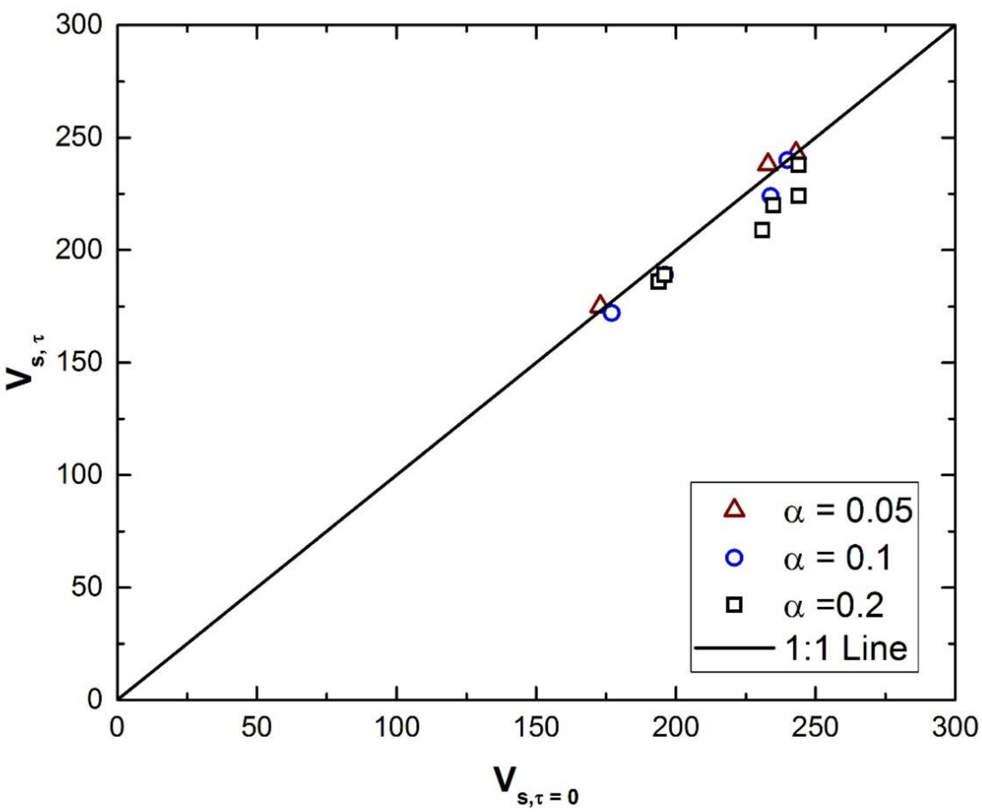

Figure 1. Shear wave velocity measurements for conducted alpha tests. $V_{s,\tau=0}$ denotes V_s collected at end of consolidation, $V_{s,\tau}$ denotes V_s collected at end of static pre-shearing.

The final stage was constant-volume stress-controlled horizontal shearing with a cyclic stress ratio (CSR) of 0.095 and frequency of 0.3 Hz. Constant volume testing of a dry specimen has been shown to be equivalent to saturated, undrained testing (Dyvik et al., 1987, Finn 1985), where the change in vertical stress during shearing is equivalent to the change in pore pressure in a truly undrained test. Constant volume conditions were maintained via a feedback loop, and are defined in this study as those that maintain a single-amplitude vertical strain of no greater than 0.025% during cyclic loading and prior to liquefaction (Basham et al., 2019). In this study, the specimen was considered liquefied once it reached 3.75% single-amplitude shear strain, a common liquefaction criterion (NRC, 1985; Porcino et al., 2008).

RESULTS OF K_α TESTING

The summary of shear wave velocity measurements collected for each specimen are presented in Figure 1. V_s was measured at the end of consolidation to K_0 conditions and measured again at the end of horizontal shearing to the target static initial stress. The results are fairly consistent: for specimens at the same relative density, V_s does not vary more than ± 10%. Moreover, the introduction of the static horizontal stress does appear to have a relatively small effect on the shear wave velocity of the specimen. The largest variation in V_s between end of consolidation $V_{s,\tau=0}$, and end of horizontal shearing, $V_{s,\tau}$, was a 10% difference. The largest variation occurred in $\alpha = 0.2$ tests, where the V_s decreased after horizontal shearing, but still remained within 10% of the $\alpha = 0$ tests.

Example results of an alpha test series of dense (D_r = 87%) specimens of PG9 at 100 kPa vertical stress and CSR = 0.095 are presented in Figure 2. Multiple identical specimens were tested at increasing alpha values starting at $\alpha = 0$, for the baseline case of level ground conditions, and sequentially increased to $\alpha = 0.1$ and $\alpha = 0.2$.

Figure 2a-2d illustrate the cyclic behavior of the gravel specimens tested, while Figure 2e-2f present the evolution of vertical strain throughout testing to ensure that constant volume conditions were maintained throughout each test in the alpha series, as recommended by Basham et al. (2019).

Effect of increasing initial static shear stress on cyclic behavior: For all gravel specimens tested, the presence of a horizontal static shear stress had an effect on the cyclic resistance as well as the excess pore pressure generated during cyclic shearing. Figure 3 details the results of each series of alpha tests with 100, 250, and 500 kPa vertical stresses.

The number of cycles required for the gravel specimen to liquefy was affected by the increase in horizontal static shear stress (Figure 3a). As the horizontal static shear stress (α) increased, specimens underwent fewer cycles of loading before triggering liquefaction (i.e., 3.75% single-amplitude shear strain). The cyclic resistance ratio, CRR, was also affected by changes in α. CRR is the horizontal shear stress at 3.75% shear strain, normalized by the vertical stress at the end of consolidation. For each series, an increase in α resulted in an increase in the shear stress required to trigger liquefaction.

The presence of a horizontal static shear stress also had an effect on the pore pressure generation of both loose and dense specimens (Figure 3c). As the static horizontal shear stress increased, the excess pore pressure generated at liquefaction triggering decreased. That is, a specimen with increasing α is more vulnerable to liquefaction and liquefies at lower pore pressure than at level ground conditions.

As shown in Figure 2a, as α increases, the single-amplitude value of shear stress increases. For $\alpha = 0.1$ and $\alpha = 0.2$, all single-amplitude shear stress remains positive, i.e., there is no shear stress reversal (for the CSR = 0.095). All specimens liquefy as they reach the ultimate state (US) line derived from monotonic testing. Figure 2c shows that as α increases, both the excess pore pressure and number of cycles required to trigger liquefaction decrease, since liquefaction and ultimate state are reached at higher shear stresses.

Similar effects of increasing α have been observed for gravelly soils using the cyclic triaxial device. For gravelly soils in cyclic triaxial tests, increasing the initial static stress resulted in an increase in the cyclic resistance ratio as well as a decrease in the excess pore pressure generated at liquefaction (Haeri et al., 2018).

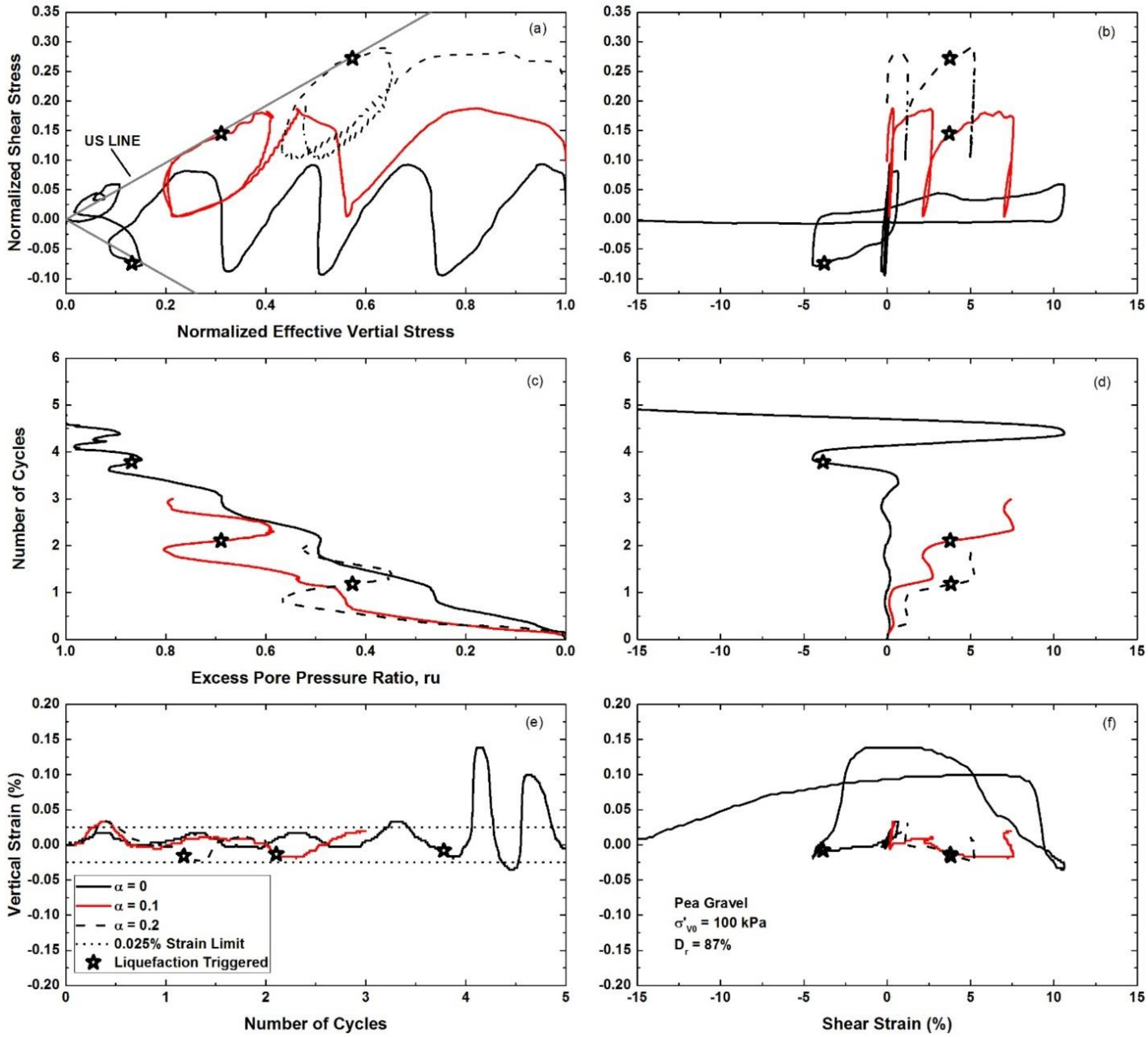

Figure 2. Cyclic shearing on PG9 specimens sheared at CSR = 0.095, 87% relative density, and 100 kPa vertical stress. a) normalized stress path response, b) shear stress-shear strain response, c) excess pore water pressure, d) shear strain evolution, e) vertical strain generation, f) vertical strain vs. shear strain.

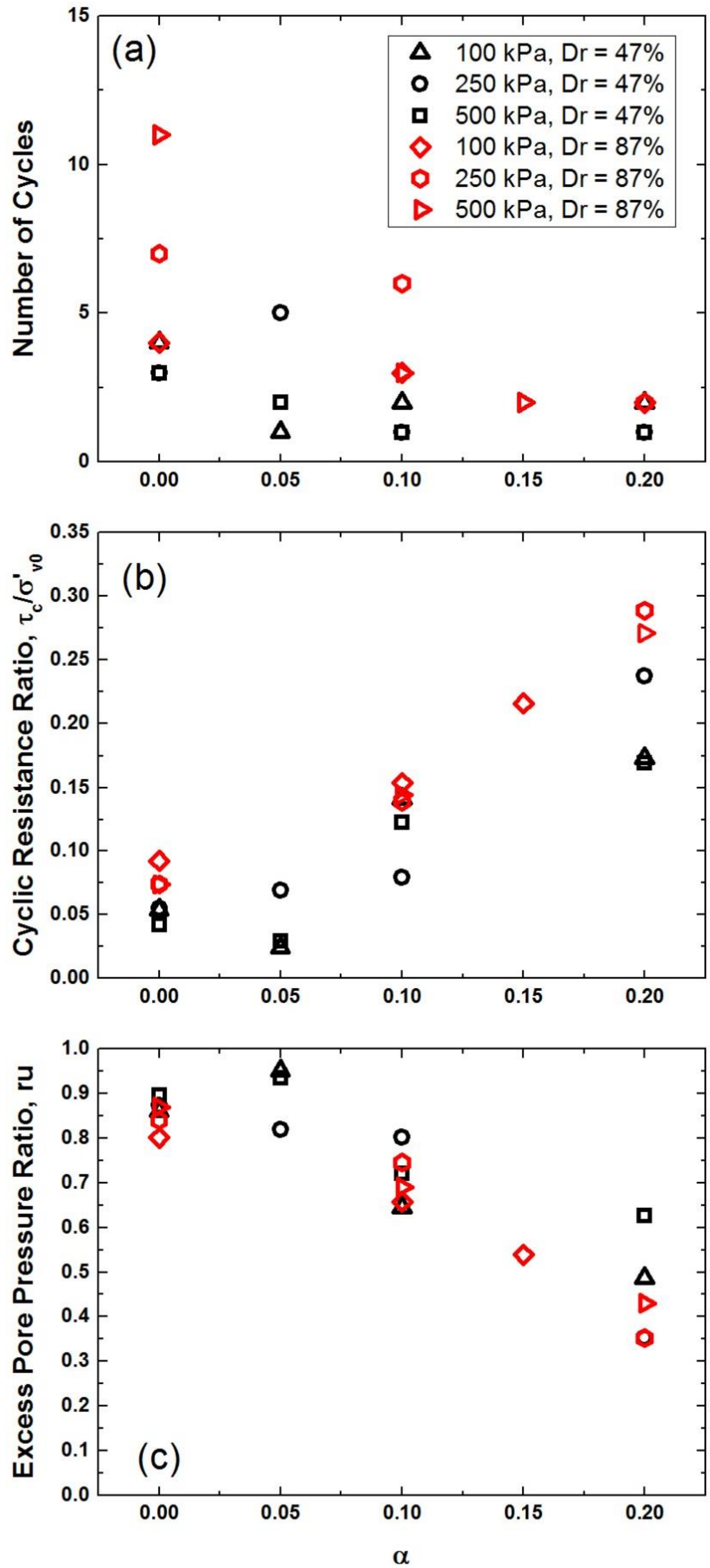

Figure 3. Effects of increasing static shear stress on a) Number of Cycles, b) Cyclic Resistance Ratio, c) Excess pore pressure generation at liquefaction

Comparable results have also been observed for sands. The presence of a horizontal static shear stress increases the resistance of the specimen to pore pressure generation (Seed, 1983; Sivathayalan and Ha, 2011), resulting in a decrease in excess pore pressure ratio as α increases. The cyclic resistance increases with increases in α for moderately dense to dense sands (Vaid et al., 2001). The number of cycles required to liquefy was shown to decrease with increasing α for sands, as the increase in horizontal stress caused a loss of specimen strength, particularly when approaching α values of 0.2 (Porcino et al., 2008).

EFFECT OF RELATIVE DENSITY, VERTICAL STRESS, AND STATIC SHEAR STRESS ON K_α

The K_α correction factor adjusts sloping ground conditions to equivalent level ground conditions. If K_α is less than 1, then the soil is more susceptible to liquefaction whereas if K_α is greater than 1, the soil is less susceptible to liquefaction compared to level ground. For the specimens tested, K_α was calculated using equation 1, where $\tau_{c,\alpha} / \sigma'_{v0}$ was calculated from the shear stress required to reach 3.75% single-amplitude shear strain at $\alpha \neq 0$, and $\tau_{c,\alpha=0} / \sigma'_{v0}$ was calculated from the level ground ($\alpha = 0$) test for each series (Figure 4).

The effects of vertical stress and relative density on K_α are presented in Figure 4. Due to limitations in maintaining constant volume conditions with higher α values, the dense 500 kPa series was tested at $\alpha = 0$, 0.1, and 0.15, and all K_α values for α greater than 0.15 were extrapolated from the available data (Figure 4c). Relative density has an effect on the cyclic response of gravels under sloping conditions. In general, and for all vertical stresses tested, dense specimens had a higher K_α value than loose specimens. For all loose specimens tested, when a horizontal static shear stress was present, K_α was less than 1, meaning PG9 is more susceptible to liquefaction in the loose state under sloping ground conditions than under level ground conditions.

The effect of vertical stress on K_α for PG9 is less pronounced. Under all conditions except for the dense case at 250 kPa vertical stress and static shear stress ratio of 0.2, the K_α values are less than 1 for both loose and dense specimens. Therefore, in general, PG9 specimens with initial static horizontal stresses are more vulnerable to liquefaction than under level ground conditions.

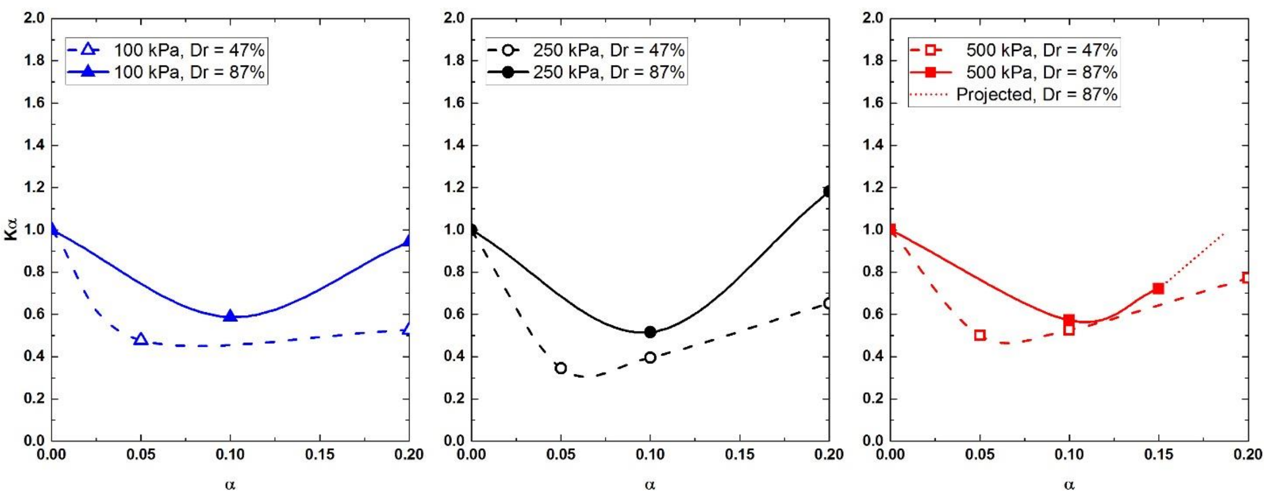

Figure 4. K_α correction values for given α values. a) 100 kPa vertical stress, b) 250 kPa vertical stress, c) 500 kPa vertical stress

CONCLUSIONS

Cyclic tests were performed on a series of specimens of loose (D_r = 47%) and dense (D_r = 87%) uniform pea gravel to assess the impact of a horizontal static shear stress on the cyclic behavior of gravelly soils. It was found that increasing α has an effect on the pore pressure generation, cyclic resistance ratio, and the cyclic resistance of the specimen. As alpha increases, the cyclic resistance ratio increases, the excess pore pressure generated at liquefaction (defined as 3.75% single-amplitude shear strain) decreases and the number of cycles required to reach liquefaction also decreases.

Additionally, relative density of the specimen has an effect on the K_α between level ground and sloping ground conditions. K_α is higher for dense specimens than for loose. However, for the gravel specimens tested (PG9), vertical stress did not appear to have a significant impact on K_α.

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