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An experimental study about the effects of the partially drained strain paths on the monotonic behavior of loose silty sands using triaxial tests

Jafar Mohammadi [a] , Siamak Zadkarim [b, *], Masoud Pourbaba [a]

[a] *Department of Civil Engineering, Maragheh Branch, Islamic Azad University, Maragheh, Iran.*
[b] *Department of Civil Engineering, Bonab Branch, Islamic Azad University, Bonab, Iran.*

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ABSTRACT

The mechanical behavior of silty sands is a crucial topic in the field of soil mechanics. However, many studies have been conducted to determine the main features of silty sand mixtures, there are some mechanisms that remain unclear. Most of the previously applied studies have focused on the behavior of silty sands under conventional paths, such as consolidated drained and consolidated undrained stress-strain paths. Recent investigations have shown the assumption that the mentioned conventional paths are critical for all situations is not accurate. Therefore, considering partially drained paths cannot only help better understand the mechanical behavior of silty sands but is also necessary to ensure the safety of projects. In this paper, 14 triaxial shear tests are applied to assess the effects of partially drained paths on the main features of the shearing mechanism of silty sands. As the water inlet is the most critical path between the partially drained tests, this research is done by considering only this type of partial drainage and ignoring other non-crucial partially drained strain paths. Achieved results indicate that partial drainage can affect the behavior of samples with a little fine content (up to 5%) significantly, while for samples with more fine content, these effects are not considerable. In other words, samples that do not exhibit a fully static liquefaction (completely softening behavior), will be considerably affected by partial drainage. Effects of water inlet during shearing on the asymptotic stress ratios, excess pore water generation, and experienced stress paths are investigated as well.

Keywords: *Partial drainage, Silty sand, Water inlet, Strain path, Asymptotic stress ratio.*

1. Introduction

The stress-strain response of soils depends on different parameters and changes in each of these parameters can influence the behavior of soils significantly [1, 2]. For example, parameters such as confining stress, void ratio, initial fabric, pattern of loading (shear mode), grain shapes, and aging situation are some of those parameters that can affect the mechanical behavior of soils [3]. Studying the effects of these parameters can help engineers enhance their knowledge in the prediction of geotechnical hazards and prepare the most effective remediation plans [4]. The liquefaction can be considered one of the most hazardous phenomena in geotechnical projects that can occur in both static and dynamic situations [3].

Under static loading conditions, loose sands show contraction behavior that leads to an increment in pore water pressure, therefore, the sand mass loses its previous stability. For saturated loose sandy soils, parameters such as fine content and the plasticity index of that fine content can considerably influence the behavior of sands. Many studies have been conducted to investigate the effects of fine content on the liquefaction potential of sands. One of the pioneering investigations in the assessment of the liquefaction potential of sands was done by Ishihara et al. [5]. In this study, undrained deformations of different types of sands and the onset of the liquefaction under monotonic and cyclic loading conditions were evaluated. It was shown that excess pore water pressure can be generated by developing plastic volumetric strains and the yield surfaces are almost independent of the stress state and density of sands. Bazyar and Dobry [6] using triaxial tests investigated the cyclic and monotonic behavior of loose saturated sands. In this research, the effects of the initial static shear stress on the undrained cyclic response of anisotropically consolidated samples were evaluated, demonstrating that the behavior of sands depends on the initial shear stress of samples. Alarcon et al. [7] using a hollow cylinder apparatus investigated the cyclic and monotonic behavior of sands with a focus on the liquefaction onset of samples. In this research, by introducing the collapse line, it was shown that the collapse of the initial fabric of sands could lead to an eventual increment in excess pore water pressure. In addition, it was indicated that differences between steady-state in the drained and undrained tests could be interpreted using the concept of the collapse line. Law et al. [8] using eight reconstituted granular samples that were prepared by fine sands, non-plastic silts, and high plastic clay materials, investigated the influences of the fine content on the stress-strain behavior of sands. The cyclic resistance of sands was studied using a triaxial apparatus in this investigation. It was shown that the strength of sands against the liquefaction cannot only be related to the physical properties of soil, such as grain distribution, void ratio, and Atterberg limits, but also is dependent on the mechanical properties of sands, including friction angle and cohesion. In addition, it was shown that sand strength will be decreased by increasing the content of non-plastic silts up to 30%; then, an increment of fine content will result in an increment of strength. However, sand samples with high plastic clay content will show a reduction in strength if the fine content is lower than 10%. By increasing clay content from 10%, the strength of sands

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* Corresponding author. *E-mail address:* S_Zadkarim@Yahoo.Com (S. Zadkarim).

against the liquefaction will be increased. Lade and Yamamuro [9] using triaxial tests investigated the behavior of saturated and unsaturated sands under drained and undrained shearing conditions. In this research, it was shown that the saturated samples will exhibit a stress path inside the instability region and the yield surface will expand along the hydrostatic line. The concept of an instability line was introduced in this research. Onyelowe et al. [10] investigated the effects of the fine content on the hydro-mechanical behavior of a compacted sub-base material. Pitman et al. [11] using mixed sands with non-plastic and plastic fine content and employing triaxial shear tests investigated monotonic consolidated undrained behavior of granular materials. It was shown that fine content can influence the stress-strain response of sand samples at large strains (strains larger than 0.5%) significantly. In addition, the applied tests revealed that the plastic fine content leads to an increment in the steady-state strength of sand for all percentages of fine content. The vanayagam et al. [12] using cyclic triaxial tests investigated the relation between the number of cycles that can result in the liquefaction and the equivalent void ratio (and void ratio). The results indicated that the microstructure of sand samples can be divided into some categories based on how fine material fills the existing voids. Polito et al. [13] using a cyclic triaxial apparatus showed that the behavior of mixed sand-silt soil relates mostly to the relative density of samples rather than the percentage of fine content. In addition, it was shown that the strength of pure sand will be larger than the mixed sand-silt samples in the same relative density. Tabrizi et al. [14] used high cyclic triaxial tests to evaluate the strain accumulation pattern of treated sands. Amini and Qi [15] investigated the effects of the sample preparation methods on the strength of the mixed sand-silt samples and indicated that different sample preparation methods will lead to the same strength against the liquefaction (however, different sample preparation methods lead to different fabric in samples). Onyelowe et al. [41, 42], and Ebid [43] reviewed and evaluated the application of the artificial intelligent methods and different constitutive relationships to analyze geotechnical problems, including the liquefaction. During the past two decades, research about mixed silty sand soils has mainly focused on their strength against the liquefaction. The threshold silt content (Karim and Alem, [16]), the relationship between equivalent void ratio and strength of sand samples (Monkul and Yamamuro [17], Baki et al. [18], Rahman et al. [19]), the effects of fine content on the stability line, collapse line, and steady-state line (Papadopoulou and Tika, [20]), the cyclic behavior of these samples (Yamamuro et al. [21], Xenaki and Athanasopoulos, 22]) and the static liquefaction of them have been studied using consolidated triaxial tests (Ranga et al. [23], Chaneva et al. [38]), simple shear tests (Porcino and Diano, [24]), hollow cylinder tests, and by numerical models (Lashkari et al. [25]). Grain size distribution and grain shapes also can affect the behavior of silty sands (Taiba et al. [26]). Monkul and Yamamuro [17] showed that grain shapes, sizes, and relative size (ratio between the median size of silt and sands) could alter the static behavior of silty sands. In this study, it was shown that the potential of liquefaction would be increased by decreasing the uniformity coefficient of silts. In addition, it was shown that a reduction in the value of D50 (sand) /D 50(silt) could lead to an increment in the potential of liquefaction.

All the mentioned investigations have been conducted by considering the undrained condition as the most critical path for silty sands. However, the recently applied research on the effects of different strain paths revealed that the partially drained strain paths can induce more softening in sand samples (Tohidvand et al. [27, 28]). The partially drained strain paths are those in which both volumetric and pore water pressure can be induced during the shearing of soils. The applied element tests on the partially drained behavior of sands can be divided into two main categories. The first one is the tests considering only the outlet of pore water using a drainage filter where the results showed that the undrained behavior is more critical than the partially drained one (Chen et al. [29], Suzuki et al. [30], Yao et al. [31], Yamamoto et al. [32], Umehara et al. [33]). The second type of test is the tests is conducted using the digital volume pressure controller apparatus which allows samples to experience both water inlet and outlet. The results of the second type of test revealed that a small volume of water inlet could lead to a considerable softening in sand samples (Vaid and Eliadorani [34], Gananathan [35], Logeswaran [36], Wu et al. [37]). In addition to the applied element tests, the results of physical modelling experiments (using a centrifuge or shaking table tests) have indicated that the assumption of the undrained condition cannot be correct even in seismic situations. Considering the partially drained condition can help to model the behavior of soil masses more precisely (Adamidis and Madabhushi, [39], Kamai, [40]).

However, some researchers assume that a partially drained condition occurs when the soil builds up excess pore water pressure less than in the fully undrained condition and drainage of water in the granular materials occur simultaneously. Some other researchers considered all paths with simultaneous volumetric strain and pore water pressure generation as the partially drained paths. For example, Eliadorani [42] stated" *In most field situations, however, the soil elements drain and experience a change in volume and pore pressure with time simultaneously. The soil response would be fully drained only if on loading the total and effective stress paths are parallel so that the loading corresponds to* $d\sigma = d\sigma'$ *and* $du = 0$ *at all times. If they are not, the deformation response should be regarded as partially drained. The undrained response that enforces zero volume change amounts to a special case of this suite of partially drained responses*". Therefore, some researchers assume partially drained paths as the paths where the generation of the pore water pressure is less than the undrained situation, while others consider them as the paths where both volumetric strains and excess pore water pressure can be generated. In this paper, we considered partially drained paths as the second definition, not the first one. Therefore, the results may be between CD and CU conditions or can exceed this limiting boundary.

However, while the partially drained behavior of pure sands has been studied in the literature comprehensively; there is a gap in knowledge about the effects of the water inlet or outlet on the mechanical behavior of silty sands. This paper investigates, using monotonic triaxial tests, the effects of different strain paths including the conventional consolidated drained and consolidated undrained tests on the behavior of loose sands. The test program, which is explained in detail in the next section, consists of partially drained paths as well.

2. Tests program and procedures

2.1. Employed materials

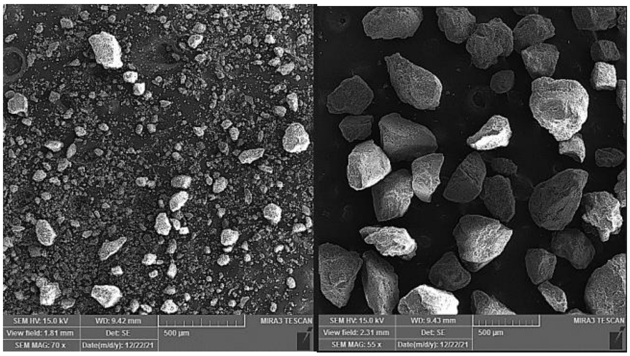
In this study, Firoozkuh No. 161 medium sand is used as the soil material. Firoozkuh No. 161 medium sand is industrially produced by crushing rocks from the Firoozkuh region in the central part of Iran and has been used for different experimental studies. The scanning electron microscope image (SEM) of the sand particles is shown in Fig. 1a and the distribution of the particle sizes is shown in Fig. 2. The main properties of the selected sand material are presented in Table 1. The non-plastic silt material employed is extracted from the riversides of the Shabester River in the northwestern part of Iran. The grain size distribution of the non-plastic silts is shown in Fig. 2, and the SEM photo of this soil is shown in Fig. 1c. The main physical properties of the employed non-plastic silts are presented in Table 1.

2.2. Test apparatus, procedure, and program

The triaxial apparatus used for the tests is shown in Fig. 3a and the schematic view of the test setup up is presented in Fig. 3b. In this paper, digital volume-pressure controllers (DVPC) are used to set the cell pressure, inject water into the sample during tests, and measure volume changes. However, despite generating both volumetric strains and excess pore water pressure in all of the non-conventional applied tests, it would be more appropriate to name the testing condition as the limited excess pore water pressure condition rather than the partially drained condition. As the partially drained tests with water inlet are the most critical strain path for samples, the research is focused on this type of partially drained test. The achieved results are compared with two conventional consolidated drained and consolidated undrained paths.

Table 1. The main properties of the used sand and silt material.

Name	Specific gravity (G_s)	Minimum void ratio (e_{min})	Maximum void ratio (e_{max})	Used relative density	Soil type
Firoozkuh No. 161 sand	2.65	0.54	0.94	30%	SP
Shabestar non-plastic silt	2.67	0.67	1.11	30%	ML



(a) (b)

Figure 1. (a) SEM photo of the used non-plastic silt (b) SEM photo of the Firoozkuh No. 161 fine sand.

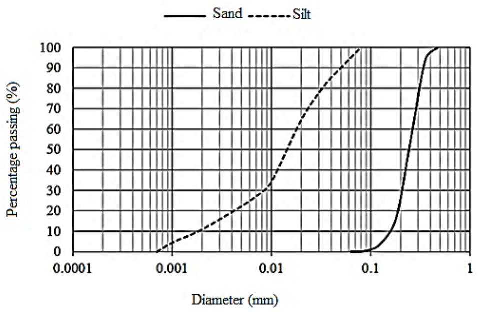


Figure 2. Grain size distribution of the used sands and silts.

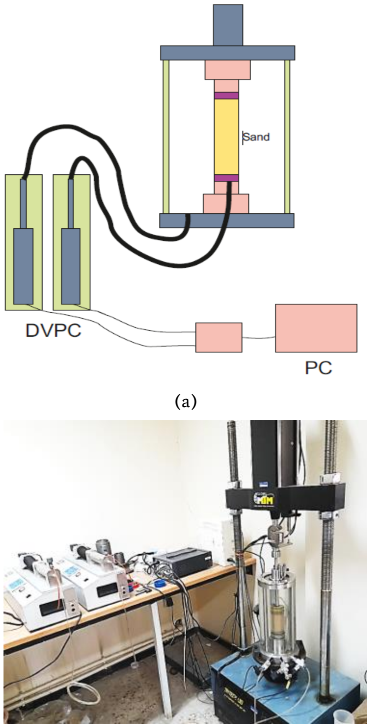
All tests were performed on both pure sands and silty sands to provide sufficient data about the effects of non-plastic silts on the behavior of partially drained sands. All samples were created using the wet-tamping sample preparation method with 7% moisture. Silty sands with 5%, 15%, and 30% fine content were employed in this study. All tests were applied in a strain-controlled manner, where consolidated undrained tests were conducted at a strain rate equal to 0.5 mm/min and consolidated drained tests were done at a strain rate equal to 0.05 mm/min. All samples were made at an initial relative density of 30% to investigate the behavior of loose sands and silty sands. The applied test program is detailed in Table2.

In Table 2, CU is used for the conventional consolidated undrained tests, CD for the conventional consolidated drained tests, and CPD for the consolidated partially drained tests. Partially drained tests were conducted using known values of the ratio $d\xi_v/d\xi_a$ (volumetric strain per axial strain) during tests. Changes in this value were applied linearly as shown in Fig. 4; therefore, the ultimate state of the soil behavior is not equivalent to the steady-state (because of the non-constant volumetric strains). In this paper, the term “asymptotic state” is used instead of “steady-state” for the ultimate behavior of partially drained tests. All samples were sheared up to axial strains of at least 20%.

3. Results

3.1. Conventional tests

In this section, the achieved results are evaluated and discussions about them are presented. Firstly, the results of the CD and CU tests for clean sands are presented. As shown in Figs. 5a and 5b, the stress ratio in both CD and CU tests are approached a constant value equal to 1.18, which corresponds to a friction angle of 29.5 degrees.



(a)

(b)

Figure 3. (a) The used triaxial apparatus (b) schematic view of the employed test setup.

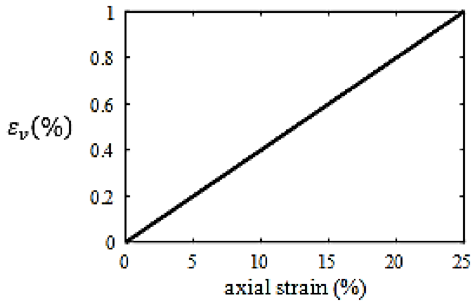
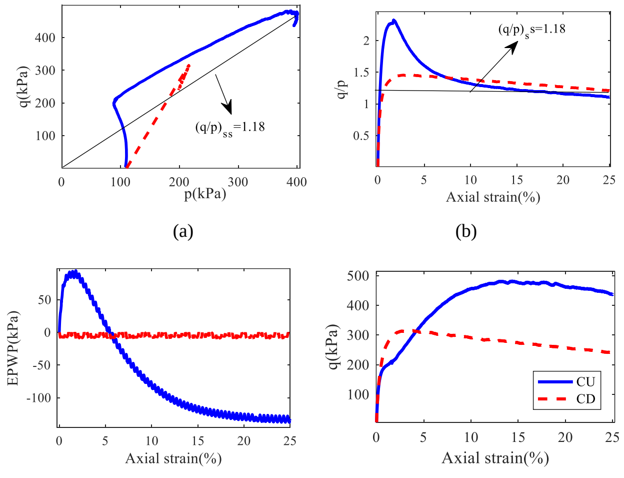


Figure 4. A sample path for linear changes of ξv in partially drained tests.

Table 2. Details of the applied triaxial test.

Name	Consolidation Stress (kPa)	Initial relative density	Type of test	$d\xi_v/d\xi_a$ (%)	Fine content (FC %)
1	110	30	CU	-	0
2	110	30	CD	-	0
3	110	30	CU	-	5
4	110	30	CU	-	15
5	110	30	CU	-	30
6	110	30	CD	-	5
7	110	30	CD	-	15
8	110	30	CD	-	30
9	110	30	CPD	0.25	5
10	110	30	CPD	0.25	15
11	110	30	CPD	0.25	30
12	110	30	CPD	0.125	5
13	110	30	CPD	0.125	15
14	110	30	CPD	0.125	30



(a) (b)

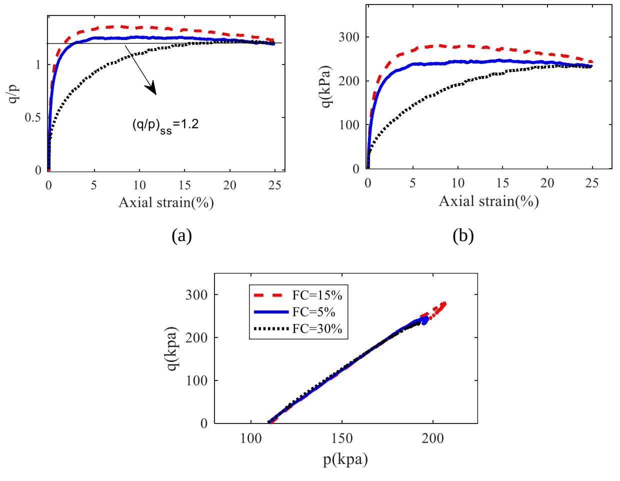
(c) (d)

Figure. 5. The results of the CD and CU tests for the clean Firoozkuh No. 161 sand. (a) Stress path (b) asymptotic stress ratio (c) excess pore water pressure (EPWP) (d) Deviatoric stress curves.

The sand specimen in the CU test exhibited higher strength against triaxial shearing and consequently resisted larger deviatoric stresses (q). Both samples in the CD and CU tests approached the steady state line by decreasing the values of deviatoric stresses. A phase transformation occurred in the CU test, where the initial contractive stress transformed into a dilative behavior. The slope of the phase transformation line is greater than that of the steady-state line, as can be found in Figure 5.

The results of the consolidated drained tests for silty sand samples are presented in Fig. 6. As shown in Fig. 6a, all three samples with fine content of 5%, 15%, and 30% show an approache to the same stress ratio in their steady-states, stood at 1.2. This value nearly equals the steady-state stress ratios in clean sands. Therefore, the presence of non-plastic fine content seems to have no significant effect on the steady-state stress ratios in the CD tests. In addition, Fig. 6b shows that an increment of fine content from 5% to 15% leads to an increment in the experienced peak deviatoric stresses. However, by increasing fine content from 15% to 30% the behavior of the silt-sand mixture completely hardens without any pre-failure peak in the deviatoric stresses. The experienced stress paths for these samples are plotted in Fig. 6c.

The results of the consolidated undrained tests for the silty sands with 5%, 15%, and 30% fine content are depicted in Fig. 7. Fig. 7. a shows an increment in the values of steady-state stress ratios compared to clean sand and drained tests of silty sands. Such an increment can be found in the results of other researchers like Papadopoulou and Tika [14], while some other researchers have not reported such a behavior in their studies. The main reason for this behavior (increment in the steady-state stress ratio) can be related to changes in the pattern of pore water pressure generation during tests. As can be found in Fig. 7d (in comparison to Fig. 5c) an increase in the amount of fine content results in more contractive behavior in samples. Such behavior was reported by almost all researchers who worked on the mechanical responses of silty sands and interpreted as a reason for the increment in the compressibility of silty sands. It can be seen in Fig. 7a that silty sand with 5% fine content has a steady-state stress ratio of 1.4, which is lower than the amount for samples with 15% and 30% fine content. The steady-state stress ratios of the samples with 15% and 30% of fine content are almost the same (equal to 2.25). Both of these two samples exhibited a completely softening behavior, while the samples of clean sand and silty sand with 5% fine content showed a phase transformation during shearing. Therefore, it can be concluded that in addition to the similar consolidated drained behavior of silty sands and clean sands, the fine content has a significant impact on the consolidated undrained behavior of samples.

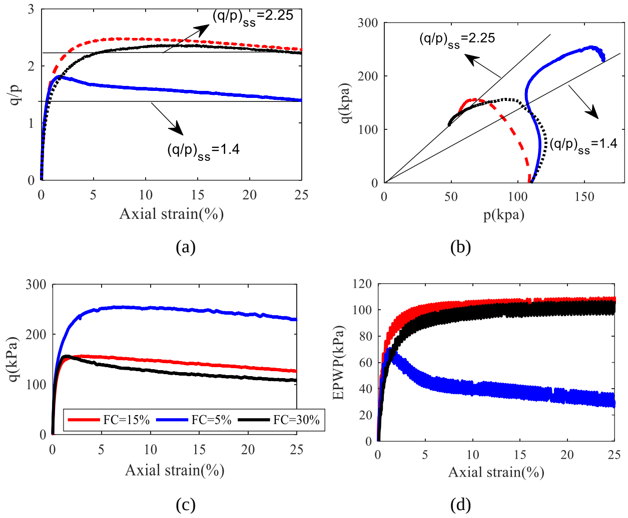


(a) (b)

(c)

Figure 6. The results of the CD triaxial tests on the silty sand with different amounts of fine content (a) asymptotic stress ratio (b) changes in deviatoric stresses (c) stress paths.

The maximum positive EPWP in the clean sand samples is almost 70kPa and the maximum negative EPWP is almost 100kPa. The silty sand samples with higher silt content (up to 30%) show more generation of positive excess pore water pressure (equivalent to more softening). Such a result corresponds to previously published results indicating that silt content (lower than the threshold value, in most cases between 25-35%) would decrease the shear strength of sands. Therefore, for specimens with %5 silts, less positive EPWP was generated compared to specimens with higher fine content. In addition, the clean sand sample demonstrated a phase transformation behavior, while such a phase transportation occurred only in samples with 5% silts. This phenomenon could indicate that softening would be magnified by increasing silt amount (till FC=30%, or the threshold value).



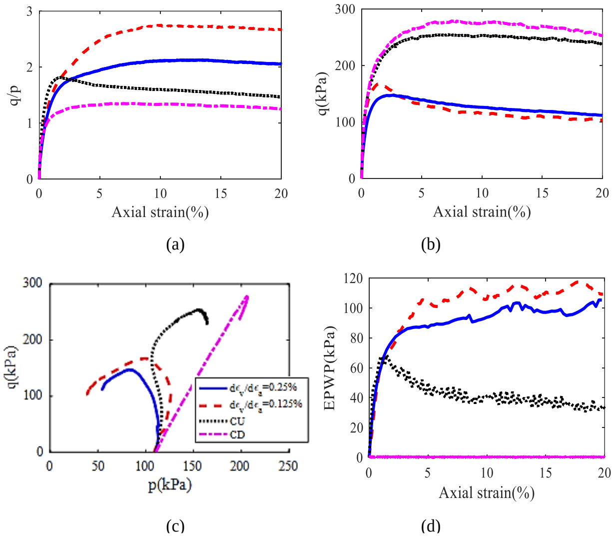
(a) (b)

(c) (d)

Figure. 7. The consolidated undrained tests on the silty sands with 5%, 15%, and 30% of fine content (a) asymptotic stress ratios (b) stress paths (c) deviatoric stresses (d) excess pore water pressures.

3.2. Partially drained tests (the limited excess pore water pressure condition) on silty sands

To investigate the effects of the water inlet on the sample during shearing which can be considered the most critical path of partially drained tests, silty-sand samples are subjected to two linearly increased $d\xi_v/d\xi_a$. Details of the selected paths were presented in the previous section. Fig. 8 shows the achieved results using silty sand samples with 5% fine content. As it can be seen in Fig. 8a, partially drained paths lead to more softening in samples where they lost 63% and 54% (for $d\xi_v/d\xi_a$ =0.25% and $d\xi_v/d\xi_a$ =0.125%, respectively) of their initial strength by the generation of excess pore water pressure. Such a softening changed the original behavior of the sample under the CU test (which has a phase transformation during the test) to the flow liquefaction. In addition, Fig. 8a shows that the asymptotic stress ratios for partially drained paths are increased; however, the peak deviatoric stresses are decreased considerably.



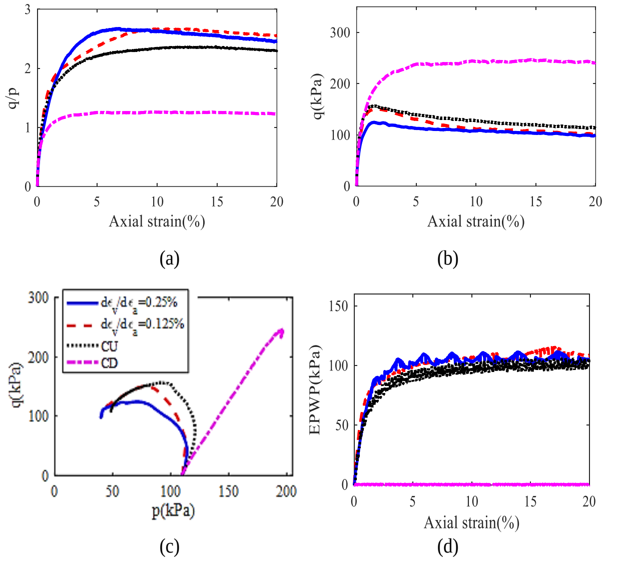
(a) (b)

(c) (d)

Figure 8. The consolidated partially drained (CPD) tests on the silty sands with 5% of fine content (a) asymptotic stress ratios (b) deviatoric stresses (c) stress paths (d) excess pore water pressures.

The effects of the partially drained strain paths with the water inlet on the behavior of silty sands with 15% fine content are shown in Fig. 9. As Fig. 9c shows, in this case, all paths (the CU and CPD) except the drained path lead to a softening without any phase transformation. In addition, the asymptotic stress ratios of the CU test and CPD tests are almost the same, which is in contrast with the samples with 5% fine content (Fig. 9a and Fig. 8a). The same behavior in the generation of excess pore water pressures for the CU and CPD paths is achieved, as shown in Fig. 9d.

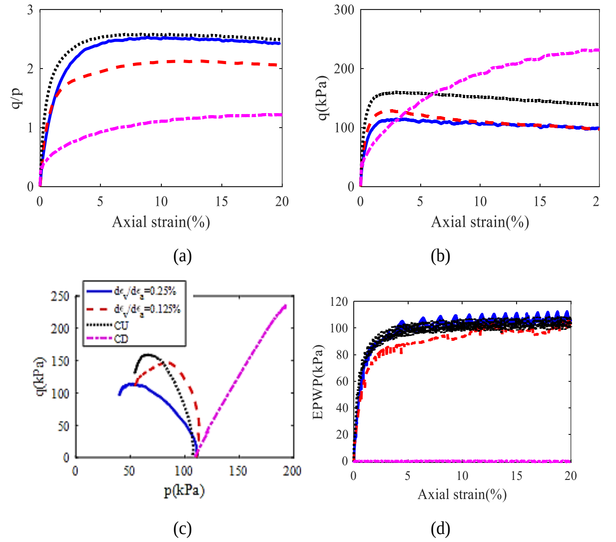
Further investigation on the effects of the partially drained paths on the monotonic behavior of silty sands is implemented using 30% fine content. The achieved results are demonstrated in Fig. 10. Same as the samples with 15% silts, the samples with 30% silts exhibited a fully softening behavior without any phase transformation. The asymptotic stress ratios for samples with no drainage and $d\xi_v/d\xi_a$ =0.25% are almost the same; however, for samples with $d\xi_v/d\xi_a$=0.125%, the asymptotic stress ratio is reduced.



(a) (b)

(c) (d)

Figure 9. The consolidated partially drained (CPD) tests on the silty sands with 15% of fine content (a) asymptotic stress ratios (b) deviatoric stresses (c) stress paths (d) excess pore water pressures.



(a) (b)

(c) (d)

Figure 10. The consolidated partially drained (CPD) tests on the silty sands with 30% of fine content (a) asymptotic stress ratios (b) deviatoric stresses (c) stress paths (d) excess pore water pressures.

4. Conclusion

Almost all previously applied studies on the behavior of silty sands have been conducted by considering the conventional drained and undrained paths as the limiting boundaries for the response of soils. Recent investigations have indicated that this assumption is not correct and partially drained paths with allowing water inlet can lead to more softening in the samples. In this paper, for the first time in the literature, the partially drained behavior of silty sands is studied under monotonic loading conditions. Only water inlet is carried out during tests as this situation provides the most critical path for samples. 14 triaxial tests on clean sand and silty sands with three different fine content (5%, 15%, and 30%) are undertaken and it is shown that the partially drained paths have more influences on samples with fewer amounts of silts, whereas samples with 15% and 30% of silts reveal nearly the same results in the CPD tests as in the CU tests. For samples with 5% silt, an increment in asymptotic stress ratios can be observed during the CPD tests, while for samples with 15% and 30% silts the exhibited change in asymptotic stress ratios is negligible. It is shown that for samples with 5% silts, the stress path with a phase transformation changes to a completely softening behavior, while for other silty sand samples, the experienced stress path does not have a considerable difference for both the CU and CPD experiments. Therefore, it can be concluded that the fine content can reduce the effects of the strain paths on the mechanical behavior of sands.

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