26 May 2010, 4:45 pm - 6:45 pm

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

AN INSIGHT TO THE EFFECT OF INITIAL STATIC SHEAR STRESS ON THE LIQUEFACTION OF SANDS

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ABSTRACT

The effect of initial static shear stress on cyclic behavior of sands has been the concern of many researchers for more than five decades. This study includes the results of a set of cyclic simple shear tests carried out on a uniform sand with relative densities of 20%, 40%, and 60%, under three different initial normal stresses of 50, 150, and 250 kPa. All tests were performed under constant volume condition. Results show that the behavior of sands due to initial static shear stress, is controlled by two contradictive elements: first one relates to the increasing dynamic shear modulus due to the initial static shear stress that ends in greater liquefaction resistance, and the second relates to the amount of irreversible shear strains which increases with greater value of driving shear stress and consequently reduces the liquefaction resistance. These elements form alternations in the value of K_α; being increased in some zones and decreased in others. New trends observed in the variation of liquefaction resistance due to the initial static shear stress, leaded the authors to define new parameters which can interpret the failure conditions and complexities of the behavior.

INTRODUCTION

The effect of initial static shear stress (ISSS) on the liquefaction potential of sand first was noticed after Niigata earthquake in 1964 where a medium dense sand beneath an oil tank did not liquefy while numerous liquefaction cases were reported for such sand in other conditions (Watanabe. 1966). Another example happened for dense sand during 1978 Miyagiken-Oki earthquake in which no settlement was observed under reservoirs (Ishihara et al. 1980).

Early researches on the effect of initial static shear on the liquefaction potential of sand in 1970's and early 1980's, like what is available from Lee et al. (1967), Seed et al. (1973) , Vaid et al. (1979), Tatsuoka et al. (1982) , and Seed (1983) give evidences for an increase in liquefaction resistance due to an increase in initial static shear stresses for samples with moderate relative densities. But further researchers, such as Vaid et al. (1983) , Vaid and et al. (1985), and Szerdy (1986) working on different sands with a wider range of initial conditions like relative density and confining pressure, showed that the presence of static shear stress would cause more complicated effect on the liquefaction potential (Harder et al. 1997). In the present study, this effect is investigated through cyclic simple shear tests on the Bablosar sand.

DEFINITIONS

Since new parameters and new approach to interpret the results are used in this study, parameters are defined separately in this section.

- α: is the Initial Static Shear Stress Ratio which is defined as τ_s/σ_{v0} where τ_s is the Initial Static Shear Stress and σ_{v0} is the Normal Consolidation Stress.

- Failure Criteria: Three distinct criteria were used to define the failure in tests; First one is the cancellation of the normal pressure (i.e. σ_v=0, which is representative for 100% excess pore pressure ratio in undrained tests). Second criteria is defined as exceeding 5% Shear Strain Double Amplitude (DA) in a cycle (γ_{DA}>5%). Third criteria is referred to approaching 5% cumulative shear strain level during cyclic loading stage (γ_{ac}>5%). The first cycle in which one of the mentioned criteria is approached is called the failure cycle and Shown by N_f.

- τ_L: is the Liquefaction Resistance of sand and is defined as the Cyclic Shear Stress Amplitude (CSS) in stress controlled test, which cause the failure in 15th cycle.

▪ K_α: is the Liquefaction Resistance Ratio which is defined as the proportion of Liquefaction Resistance for a sample with the Initial Static Shear Stress, to the Liquefaction Resistance for the same sample with α=0:

$$K_\propto = \frac{(\tau_L)_\propto}{(\tau_L)_{\propto=0}} \quad (1)$$

▪ $(G)_n$: is the Cyclic Shear Modulus for $(n)^{th}$ cycle and can be calculated for each cycle from dividing the Cyclic Shear Stress Double Amplitude (which is constant in stress controlled tests) by the Cyclic Shear Strain Double Amplitude (DA) in the same cycle.

▪ $(R_{ex})_n$: is the Shear Strain Expansion Factor for $(n)^{th}$ cycle and can be calculated from dividing the difference between Shear Strain Double Amplitude in $(n+1)^{th}$ cycle and Shear Strain Double Amplitude in $(n-1)^{th}$ cycle, by the Shear Strain Double Amplitude in $(n)^{th}$ cycle (see Fig. 1):

$$(R_{ex})_\mathrm{n} = \frac{(n+1)^{th}\ cycle\ width - (n-1)^{th}\ cycle\ width}{n^{th}\ cycle\ width} \quad (2)$$

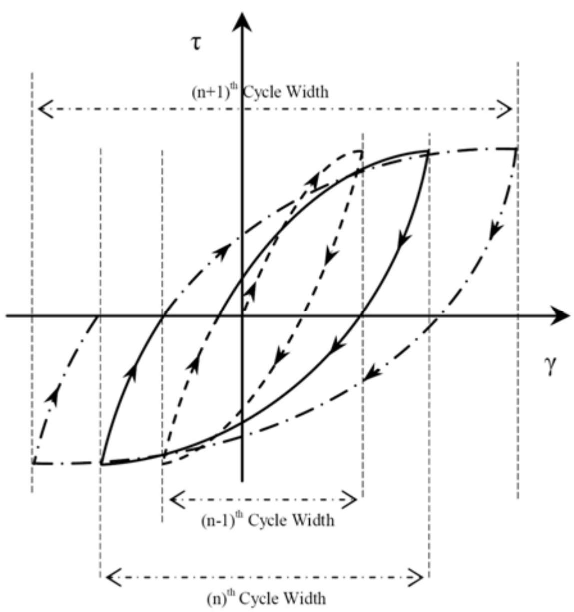

Fig. 1. Schematic definition of $(R_{ex})_n$.

▪ $(R_{ac})_n$: is the Shear Strain Accumulation Factor for $(n)^{th}$ and can be calculated for each cycle from dividing the Cycle Center Shift (Shown in Fig. 2) by the Cyclic Shear Strain Double Amplitude in the same cycle:

$$(R_{ac})_\mathrm{n} = \frac{Cycle\ Center\ Shift\ for\ (n)^{th}\ cycle}{n^{th}\ cycle\ width} \quad (3)$$

▪ $(G)_{10}$, $(R_{ex})_{10}$ and $(R_{ac})_{10}$: respectively are the Cyclic Shear Modulus, Shear Strain Expansion Factor and Shear Strain Accumulation Factor, all calculated in 10^{th} cycle of a specific cyclic loading test.

▪ $(G)_{L10}$, $(R_{ac})_{L10}$ and $(R_{ex})_{L10}$: respectively are the Cyclic Shear Modulus, Shear Strain Expansion Factor and Shear Strain Accumulation Factor , all calculated in 10^{th} cycle, when the failure occurred in 15^{th} cycle.

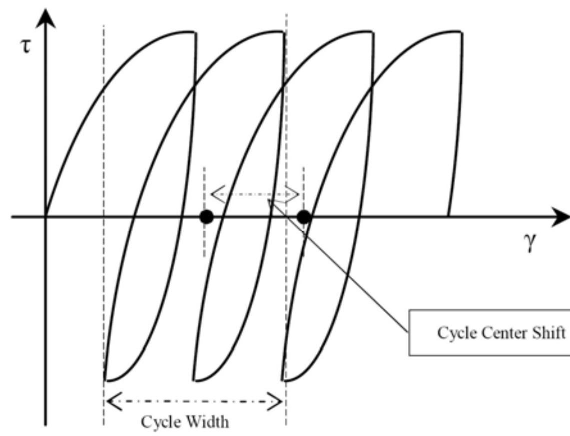

Fig. 2. Schematic definition of $(R_{ac})_n$.

TEST PROGRAM

As recent researchers have evidenced, direct shearing tests are more reliable for modeling the large scale cyclic behavior of sands (Ishihara 1993, Hosono et al. 2004.). So stress controlled cyclic simple shear tests were employed in this study. All tests were performed under constant volume condition which is more suitable when large number of tests is programmed. Tests were conducted on Babolsar sand samples, of which index parameters are presented in table 1.

Table 1. Index properties of Babolsar Sand

Specific Gravity, G_s	2.74
Maximum void ratio, e_{max}	0.77
Minimum void ratio, e_{min}	0.56
Effective grain size, D_{10} (mm)	0.14
Mean grain size, D_{50} (mm)	0.22
Uniformity coefficient, C_u	1.8
Coefficient of gradation, C_c	1.0

The specimens were cylindrical with 70 mm diameter and 20 mm height. Because of the wide range of approachable porosity and the consistency with the constant volume tests, Moist Tamping method was applied to prepare samples (Ishihara 1993, Lee et al. 1967). Samples were initially consolidated under normal stress and then having the normal load constant, initial static shear stress was applied.

Afterwards, the sample was tested under stress controlled cyclic simple shear loads with a frequency of 1 Hz. The cyclic stage was performed under constant volume condition in which the variation of normal stress (σ_v) can be a representative for excess pore pressure changes in undrained tests. Table 2 presents the value of initial conditions considered in the tests in which D_r is relative density after consolidation, σ_{v0} is initial normal stress, and α is the initial static shear stress ratio defined in previous section.

For each set of initial conditions, at least three distinct tests with different cyclic shear stresses were conducted which leads to more than 180 distinct experiments.

TEST RESULTS

Figure 3 and 4 illustrate the hysteresis graph for two selected set of tests. Figure 3 shows the results for tests with σ_{v0}=140 kPa, D_r=40%, and α=0.0, and three various Cyclic Shear Stress Amplitude (CSS), and figure 4 is for samples with the same initial condition but α=0.3.

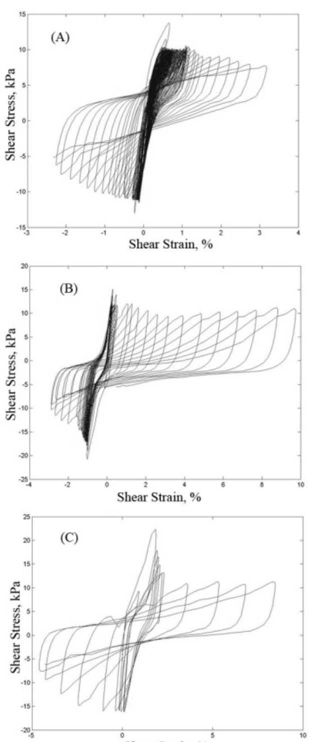

Fig. 3. Hysteresis graphs for sample with Dr=40%, σ_v=150 kPa, α=0.0, and Cyclic Shear Stress of; A)10 kPa, B)12 kPa, C)15 kPa

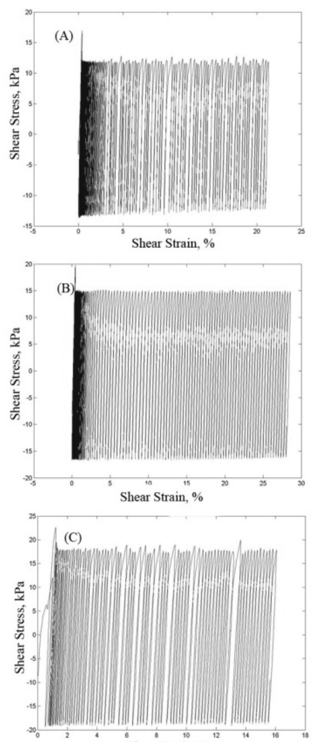

Fig. 4. Hysteresis graphs for sample with Dr=40%, σ_v=150 kPa, α=0.3, and Cyclic Shear Stress of; A)12 kPa, B)15 kPa, C)18 kPa

Figures like these, show that applying ISSS would cause obvious changes in hysteresis behavior of samples; Cyclic Shear Strain Amplitude increases during the cyclic loading stage for samples with α=0 which indicate the degradation of Cyclic Shear Strength, whereas the accumulation of irreversible shear strain is dominant in the presence of ISSS. The variation of Normal Stress Ratio (Normal Stress at any time divided by the Initial Normal Stress) for these tests are also illustrated in figures 5 and 6. These figures show that the cancellation of Normal Stress (representative for 100% excess pore pressure ratio) is not approached in presence of ISSS which is reported by other researchers too (Vaid et al. 1983).

Table 2. Initial conditions considered in experiments

Initial normal stress, σ_{v0}	*50, 150, 250 kPa*
Relative Density, D_r	*20%, 40%, 60%*
Initial static shear stress ratio, α	*0.0, 0.05, 0.1, 0.2, 0.3*

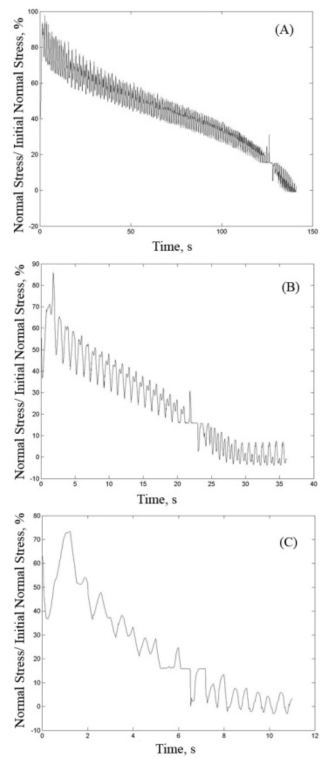

Fig. 5. Variation of Normal Stress Ratio for sample with Dr=40%, σ_v=150 kPa, α=0.0, and Cyclic Shear Stress of; A)10 kPa, B)12 kPa, C)15 kPa

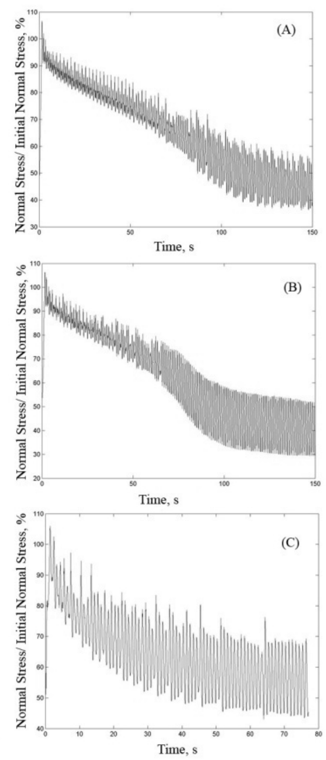

Fig. 6. Variation of Normal Stress Ratio for sample with Dr=40%, σ_v=150 kPa, α=0.3, and Cyclic Shear Stress of; A)10 kPa, B)12 kPa, C)15 kPa

Regarding 3 failure criteria defined in previous section, the failure cycle number for each criterion was drawn out for each test and the prior one is reported as the Failure Cycle Number (N_f). Table 3 contains these results for the mentioned tests conditions. As mentioned before, applying ISSS would cause the Accumulative Shear Strain Level (N_{ac}) to become controlling criterion.

Table 1: Approaching Cycle Number for different failure criteria

Sample Name	Normal Stress Ratio=0	Cycle Width > 5 %	Cumulative Strain> 5 %	Controlling Criteria	Min. Normal Stress Ratio %	Failure Cycle Number
150-40%-0.0-10	136	140	N.R*	1**	1.03***	136
150-40%-0.0-12	27	28	32	1	-3.84	27
150-40%-0.0-15	8	8	9	1,2	-3.01	8
150-40%-0.3-12	N.R	N.R	94	2	36.321	94
150-40%-0.3-15	N.R	N.R	85	2	29.401	85
150-40%-0.3-18	N.R	N.R	29	2	43.078	29

* N.R: Criterion is not reached
** 1: Normal Stress Ratio=0, 2: Cycle Strain Double Amplitude >5%, 3: Cumulative Shear Strain >5%
*** Minimum Normal Stress Ratio reached during the test

Test results also reveal that the first two criteria (cancellation of normal stress and 5% shear strain double amplitude) take place in identical or very close cycle numbers which is also reported by other researchers like Hosono et al. (2001), and Rahhal et al. (2000).

The data obtained from the cyclic tests will lead to graphs like figure 7 which illustrate the variation of Failure Cycle Number (N_f) with cyclic shear stress amplitude (CSS) for test conditions presented in Table 3. According to the previous section, Liquefaction Resistance (τ_L) and K_α is calculated for each set of initial conditions. Gathering all the results, graphs shown in figure 8 are formed in which the variation of K_α due to Initial Static Shear Stress Ratio (α) for various values of Initial Normal Stress (σ_{v0}) and Relative Density (D_r) is shown. A general trend can be denoted with the increase in K_α due to an increase in α for samples under an Initial Normal Stress of 50 kPa. However more complex behavior can be seen for Initial Normal Stress of 150 kPa and 250 kPa.

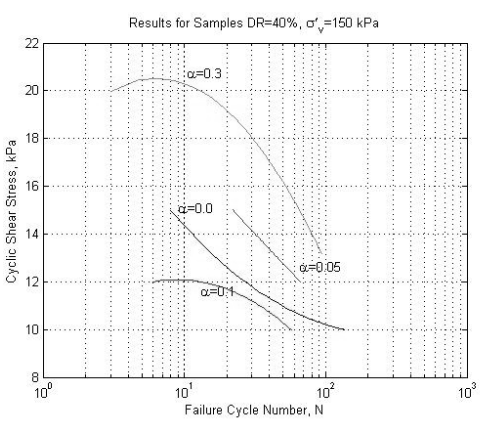

Fig. 7. Variation of Failure Cycle Number (N_f) with cyclic shear stress amplitude (CSS) for test with Initial Normal Stress of 150 kPa and Relative Density of 40% and various Initial Static Shear Stress Ratio (α)

Approaching to the considered failure criteria, three different elements seem to be more influential and need special attention to pay to:

The first element is the order of Cyclic Shear Strain Amplitude in cycles; wider Strain amplitude would cause faster approach to the first and second failure criteria (i.e. σ_v=0 and γ_{DA}>5%). $(G)_{L10}$, as defined in Definition Section, would be a suitable representative for this element. The variation of this parameter due to α is shown in figure 9 for different values of Initial Normal Stress (σ_{v0}) and Relative Density (D_r).

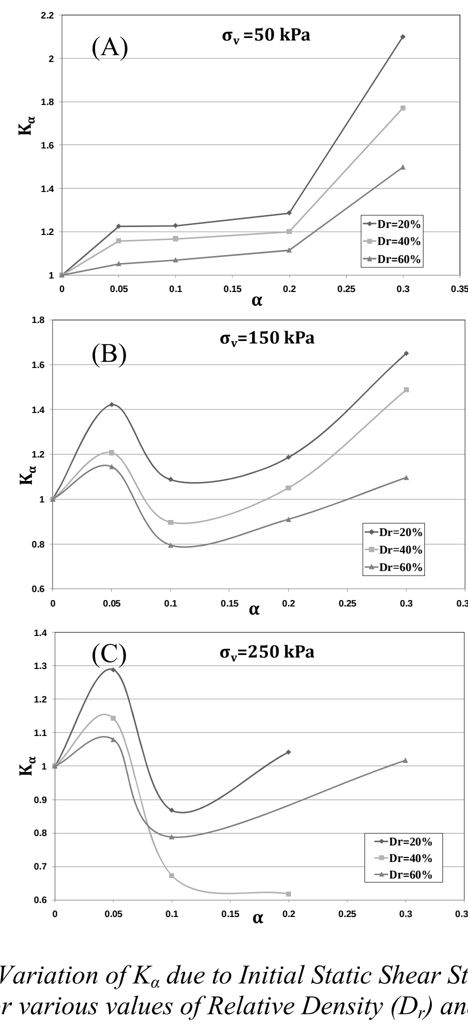

Fig. 8. Variation of K_α due to Initial Static Shear Stress Ratio (α) for various values of Relative Density (D_r) and Initial Normal Stress (σ_{v0}) of; A) 50 kPa, B) 150 kPa, and C) 250 kPa

The second element is the rate of Cyclic Shear Strength Degradation during the cyclic loading stage which causes the greater cyclic shear strain amplitude in consequent cycles and cycles *Expand* in hysteresis graph during the cyclic loading.

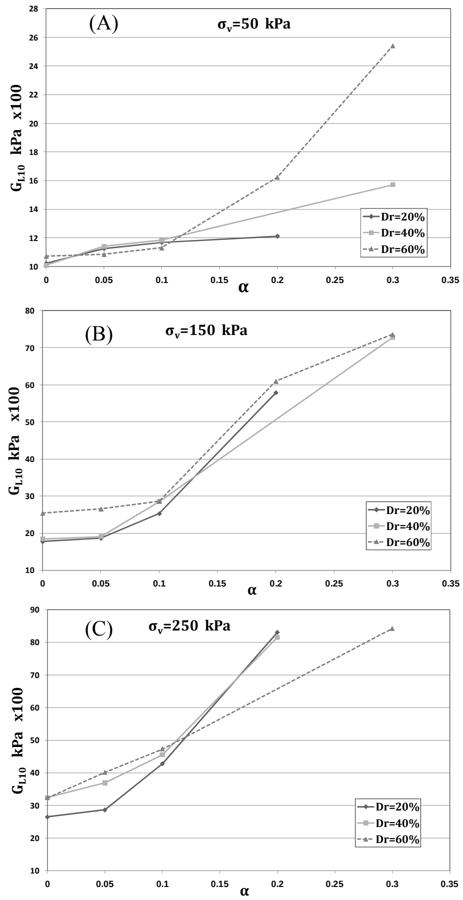

Fig. 9. Variation of $(G)_{L10}$ due to Initial Static Shear Stress Ratio (α) for various values of Relative Density (D_r) and Initial Normal Stress (σ_{v0}) of; A)10 kPa, B)12 kPa, C)15 kPa

The procedure defined in Definition Section was employed to calculate $(R_{ex})_{L10}$ which expresses the rate of Cyclic Shear Amplitude Expansion and would be a well representative for Shear Strength Degradation in Stress controlled tests. The variation of this parameter due to α is shown in figure 10 for different values of Initial Normal Stress (σ_{v0}) and Relative Density (D_r).

The third element affecting the failure procedure is the rate of accumulation of irreversible cyclic shear strain of which greater value would ease the approach to the third failure criterion (i.e. γ_{ac}>5%). This element is also presented by the new defined parameter $(R_{ac})_{L10}$ calculated as defined in Definition Section and its variation due to α is shown in figure 11 for different values of Initial Normal Stress (σ_{v0}) and Relative Density (D_r).

DISCUSSION

As mentioned before, for an initial normal stress of 50 kPa a general trend can be denoted with the increase in K_α due to an increase in α. Previous researchers rarely worked on the α- K_α relation for low confinement such as σ_{v0}=50 kPa (which is relatively representative for a confining pressure of 30 kPa in triaxial tests). Thus, comparison would be almost inconvenient in this case. Although previous studies report a decrease in liquefaction resistance in presence of initial static driving shear for loose sandy soils, but low confinement can make the loose sand to behave like a dilative soil.

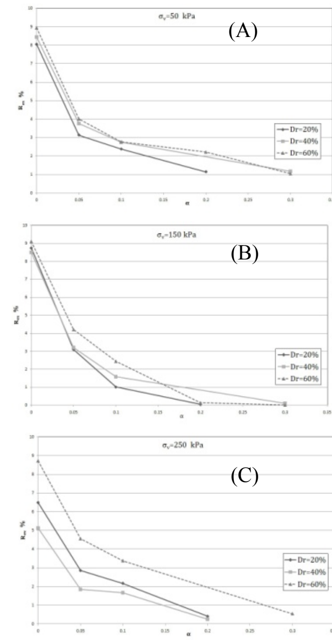

Fig. 10. Variation of $(R_{ex})_{L10}$ due to Initial Static Shear Stress Ratio (α) for various values of Relative Density (D_r) and Initial Normal Stress (σ_{v0}) of; A)10 kPa, B)12 kPa, C)15 kPa

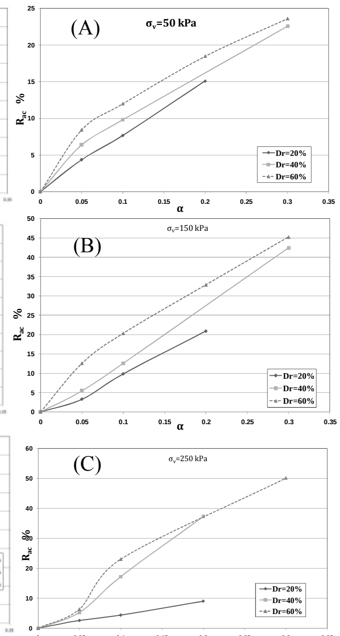

Fig. 11. Variation of $(R_{ac})_{L10}$ due to Initial Static Shear Stress Ratio (α) for various values of Relative Density (D_r) and Initial Normal Stress (σ_{v0}) of; A)10 kPa, B)12 kPa, C)15 kPa

According to the graphs in figure 8, the behavior of K_α~α graphs can be divided to three distinct zone shown schematically in figure 12; during the first zone, K_α increases moving from α=0.0 to α=0.05 (A to B), but in the second zone K_α decreases (or stay relatively constant) moving from α=0.05 to α=0.1 (B to C), and at last in the third zone K_α increases again for α>0.1 (C to D). In further lines, we try to explain these complex behaviors.

First Zone, 0.00< α <0.05 (A to B):

The Liquefaction Resistance Ratio (K_α) increases as α increases from zero to a small value (α=0.05 in this study). This happens as a result of a change in controlling failure criterion. Regarding figure 11, for the point A (i.e. α=0.0),

$(R_{ac})_{L10}$=0 which means no strain accumulation occurs when ISSS is not applied, and $(R_{ex})_{L10}$ has its maximum value (figure 10) which means the strength degradation and shear strain amplitude expansion is faster and consequently the first two failure criteria are dominant at the point A. Moving from point A to point B (i.e. α=0.0 to α=0.05), however the change of $(G)_{L10}$ value is negligible (see figure 9), a meaningful change in $(R_{ac})_{L10}$ and $(R_{ex})_{L10}$ occurs; applying ISSS caused a sudden fall in $(R_{ex})_{L10}$ which would end in slower rate of shear amplitude expansion (figure 10). On the other hand, the noticeable increase in $(R_{ac})_{L10}$ value (figure 11), makes the shear strain accumulation procedure to be dominant. These two elements, together, impose a change in failure criterion and the third failure criterion will be controlling in this point. This change in controlling failure approach ended in a raise in K_α value.

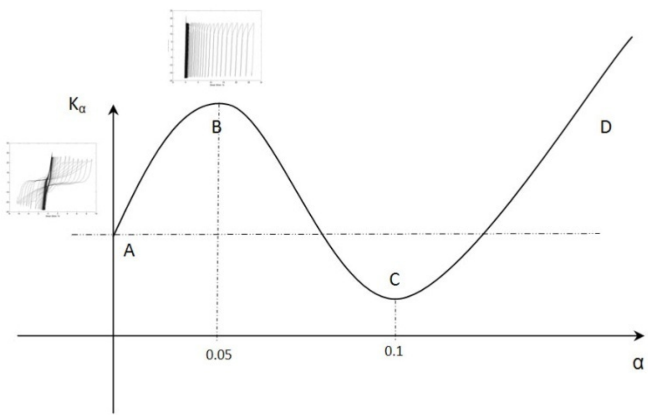

Fig. 12. Schematic for General Trend of K_α~α graphs

However other researchers rarely worked on small values of ISSS like α=0.05, but it seems that the behavior of K_α~α graphs in this zone highly depends on the definition of failure criteria and tested material. Although the change in controlling failure criteria will happens anyway but it may not lead to the described increase in K_α value.

Second zone, 0.05< α <0.10 (B to C):

According to figure 10, value of $(R_{ex})_{L10}$ continue falling and the effect of Shear Strain Amplitude Expansion is not influential in this zone. On the other hand, two other parameters, $(R_{ac})_{L10}$ and $(G)_{L10}$ both increase in this zone (figures 9 and 11). The increase in $(G)_{L10}$ due to α, means that higher values of ISSS would enhance the cyclic shear strength of samples which would consequently enhance the Liquefaction Resistance of sample by reducing cyclic shear strain amplitude.

As mentioned before, third failure criteria (reaching 5% accumulative cyclic shear strain) is controlling in this zone. So the increase in strain accumulation rate, $(R_{ac})_{L10}$, for higher values of ISSS, would speedup the approach to the third failure criteria and consequently reduce the liquefaction resistance of sample.

Therefore, two contradictive elements affect the variation of K_α due to ISSS in presence of ISSS. Depending on which one of this elements is dominant, the behavior of K_α ~ α graph would be increasing or decreasing.

Being precise about figures 9 and 11, we will find that for Initial Normal Stresses of 150 kPa and 250 kPa the increase in $(G)_{L10}$ from α=0.05 to α=0.10 is still very low where the increase in $(R_{ac})_{L10}$ is noticeable in this zone. Therefore, the effect of increase in Strain Accumulation rate would be dominant and K_α decreases.

But for Initial Normal Stresses of 50 kPa, the value of $(G)_{L10}$ is raising with an almost constant rate in this zone (see figure 9a) and $(R_{ac})_{L10}$ value would increases too (see figure 11a). These two contradictive elements will neutralize each other's effect which would lead to a relatively constant value of K_α in this zone (see figure 8a). This constant trend would extend to a part of next zone too.

Third zone, 0.10< α <0.3 (C to D):

The confliction between two contradictive elements continue in this zone too, as figures 9 and 11 show that the increasing rate of $(G)_{L10}$ become more intense in this zone for samples with Initial Normal stresses of 150 kPa and 250 kPa, and $(R_{ac})_{L10}$ values go on with their raising rate too.
The trend of K_α ~ α graph in this zone (see figure 8) evidences that the effect of higher value of cyclic shear strength, $(G)_{L10}$, is dominant for α<0.10 which caused the increase in K_α. However, as mentioned before, the relatively constant value of K_α continues till α=0.20 for samples under an Initial Normal Stress of 50 kPa and the increasing zone begins afterwards.

Figure 8 also suggest higher values of K_α for samples with smaller Relative Densities, under identical other conditions. This happens as a result of more sensitivity of looser samples with respect to stress conditions which lead in more intense change in behavior of samples due to varying stress conditions.

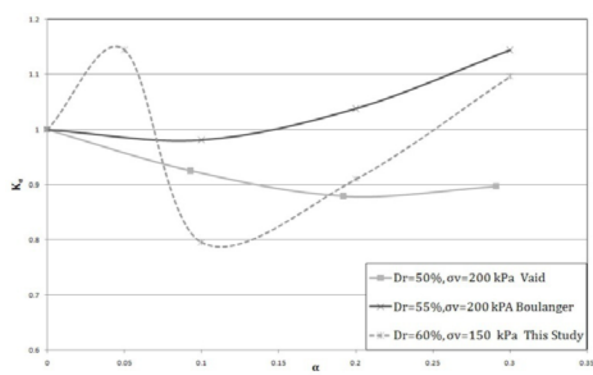

Fig. 13. Comparison between result of the previous researchers and this study

A comparison between results from this study and previous researches for similar initial conditions is illustrated in figure 13 which indicates a relative agreement between the results. However the differences in soil types and values for tested α, caused some differences in details. It should be specially noticed that since other researchers did not consider low values of ISSS (like α=0.05 in this study), the peak value in this zone is not reported by them.

CONCLUSIONS

In this research, the effect of static driving shear stress on the liquefaction resistance of Babolsar sand samples has been investigated. The results were compared to that reported by previous researchers and following conclusions can be made:

1. Applying a small value of α (e.g. α=0.05 in this study), for all cases, would cause a change in controlling failure criterion which results in a raise in K_α.

2. Since the rate of shear strain accumulation and cyclic shear strength both increases with α, initial static shear stress would cause two contradictive effects on liquefaction resistance for α>0.

3. The general trend of K_α - α graphs can be divided to three distinct zone; in the first zone (0.00< α <0.05), an increase in the K_α would happen as a result of the change in controlling failure criteria. In the second zone (0.05< α <0.10), the dominance of the raise in shear strain accumulation rate would cause a fall in K_α, and in the third zone (0.10< α <0.3), the K_α would increase again since the effect of the raise in cyclic shear strength is dominant.

4. For cases under low confinement (i.e. σ_{v0}=50 kPa in this study) the contradictive effect of increasing the cyclic shear strength and strain accumulation rate would neutralize each other for α=0.05 to α=0.2, which results in relatively constant value for K_α in this zone. However, after that for α>0.2 the effect of increase in cyclic shear strength would be dominant which cause the raise of K_α.

5. For the same other initial conditions, higher values of K_α would happen for looser samples.

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