Evaluation of the 5% double amplitude strain criterion

Évaluation du critère des 5% déformation double d'amplitude

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ABSTRACT
Cyclic triaxial tests have been widely used to determine the liquefaction susceptibility of soils in the laboratory. Tests have been mostly performed on clean sand and silty/clayey sand where the specimens are reconstituted in the lab. Two major criteria have been used to define liquefaction: 1) loss of effective confining pressure due to excess pore pressure build up (usually referred to as initial liquefaction) and 2) 5% double amplitude strain (± 2.5% axial strain) with the later being the more popular choice in recent years. This paper compiles results from the literature and research by the author to address the applicability of using the 5% double amplitude strain criterion for liquefaction with the recent growth in testing non-traditional geo-materials.

RÉSUMÉ
Les essais cycliques triaxiaux ont été largement utilisés pour déterminer la susceptibilité de liquéfaction des sols dans le laboratoire. Ces essais ont été réalisés la plupart du temps sur du sable propre aussi bien que sur du sable argileux où les spécimens sont reconstitués dans le laboratoire. Deux critères principaux ont été employés pour expliquer la liquéfaction: 1) perte de pression d'emprisonnement effectif due à l'accumulation excessive de pression de pore (habituellement désignée sous le nom de la liquéfaction initiale) et 2) 5% déformation d'amplitude double (déformation axiale ± 2.5%), le choix postérieur étant le plus populaire ces dernières années. Cet article se compile aux résultats de la littérature pour adresser l'applicabilité d'employer le 5% déformation d'amplitude double comme un critère pour la liquéfaction surtout avec la croissance récente des tests sur les géomatéreaux non traditionnels.

Keywords : Liquefaction criteria, 5% double amplitude strain, Initial Liquefaction, Cyclic Resistance, Cyclic triaxial testing

1 INTRODUCTION

The cyclic triaxial test is the most widely used laboratory test to evaluate the liquefaction potential of a soil (e.g. Silver et al., 1976; Ladd, 1977; Polito, 1999; El Mohtar et al. 2008; etc.). When a specimen is subjected to repeated shear loading, the sand particles tend to rearrange their stacking into a denser state. When drainage is prevented (similar to field conditions during an earthquake), this would result in generation of pore pressures and loss of effective stresses.

Sand or sand-fines specimens are usually prepared by air pluvation or wet tamping followed by flushing with water, or by wet deposition method (no flushing is needed). The specimens are then back-pressure saturated and consolidated to the desired effective confining stress. The specimens are then sheared undrained by applying a constant cyclic stress (measured as a cyclic stress ratio CSR). The CSR is calculated as shown in Eq. 1. The loading is usually a sinusoidal load with stress reversal applied at a frequency of 1 Hz. The excess pore pressure and axial strains are monitored during the cyclic loading until liquefaction.

$$CSR = \frac{\tau}{\sigma_o^{'}} = \frac{1}{2}\frac{\sigma_1 - \sigma_3}{\sigma_o^{'}} \qquad \text{Eq. 1}$$

Where: τ is the maximum shear stress applied at the center of the specimen on a plane with 45^o inclination, σ'_o is the confining pressure at the end of consolidation and σ_1 - σ_3 is the vertical deviatoric stress applied during the cyclic loading (single amplitude).

The specimens are usually tested at different CSR values and the results plotted versus the number of cycles to liquefaction. The Cyclic Resistance Ratio (CRR) is determined as the cyclic stress ratio (CSR) resulting in liquefaction at a given number of cycles. For an earthquake with a magnitude of 7.5, Seed and Lee (1966) defined CRR as the CSR that would result in liquefaction after 15 cycles while Ishihara (1993) used 20 cycles.

Researchers have adopted two different criteria for determining when liquefaction occurs: initial liquefaction and 5% double amplitude axial strain. Seed and Lee (1966) defined liquefaction as the number of cycles at which the excess pore pressure is equal to the initial effective confining pressure (Initial Liquefaction). On the other hand, Ishihara (1993) defined liquefaction based on axial strain; a specimen liquefies when the axial strain reaches 5% double amplitude strain (± 2.5% axial strain). These two criteria are the most widely used for defining liquefaction in cyclic triaxial tests with the 5% double amplitude strain being the more widely used. However the 5% double amplitude strain criterion was developed for natural soils where the soils experience limited cyclic mobility until the initial liquefaction (or shortly before) followed by excessive deformation (flow liquefaction). This raise a question about the applicability of the 5% double amplitude strain when testing non-traditional geo-materials such as cement grouted sands, sands with thixotropic pore fluids and sand with colloidal silica grouting where the cyclic response can be different than that of traditional soils.

2 LIQUEFACTION OF TRADITIONAL SOILS

2.1 *Cyclic response*

Figure 1 shows a typical cyclic response for clean sand tested under cyclic loading using cyclic triaxial testing. The results shown are for Ottawa sand (ASTM C778 well graded) with a relative density of 35% sheared under a CSR of 0.15. The sand was back pressure saturated (B=0.99) and sheared under sinusoidal loading pattern starting with a compression cycle. The pore pressure buildup is relatively uniform until the specimen loses about 70 – 80% of its initial effective stresses; the effective stresses drops rapidly after that to reach zero. The axial strains remain minimal through the first phase of pore pressure generation and then increase significantly once the specimen approaches initial liquefaction. Similar behavior is reported in the literature for a large range of sands and silty sands.

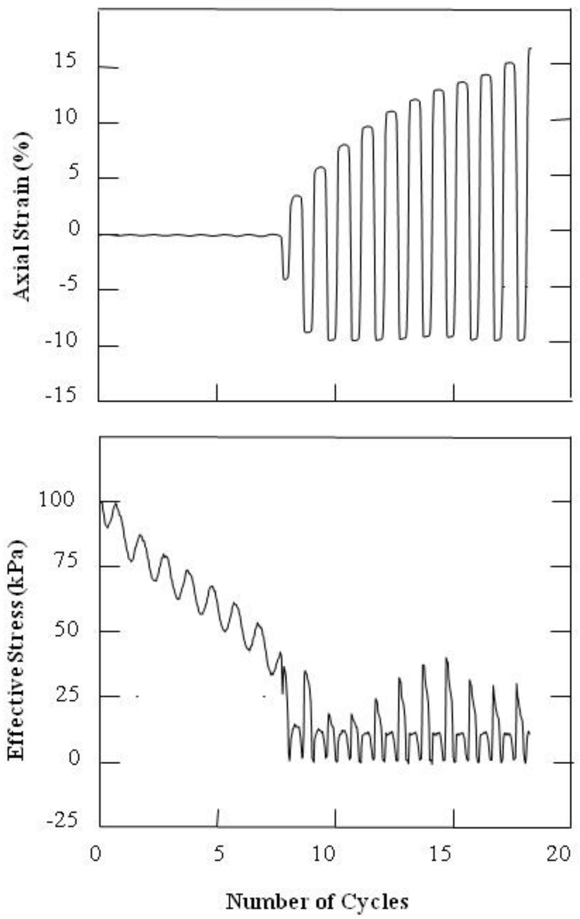

Figure 1. Cyclic behavior of sand under cyclic loading

Similar trends were reported by Georgiannou et al. (1991) for clayey sands under undrained cyclic triaxial loading. Georgiannou at al. tested Ham River sand sedimented into a kaolin suspension as well as reconstituted clayey sand form the Gullfaks (referred to as HK and GULL in Figure 2 below). The figure shows the cumulative axial strain (single amplitude) and excess pore pressure at the maximum shear stress in each cycle. The loss of confining pressure with increasing loading cycles leads to higher CSR (since the applied cyclic loading remains constant and the effective stress decreases) which is reflected in accelerated excess pore pressure and axial strain buildup. The increase in rate of axial strain and excess pore pressure generation occurs simultaneously and the number of cycles to reaching initial liquefaction or 5% double amplitude strain would be very similar.

2.2 *Comparison between different liquefaction criteria*

In their paper "Cyclic Triaxial Strength of Standard Test Sand", Silver et al. (1976) compared the results obtained using 10% double amplitude strain and initial liquefaction (loss of confining effective pressure) as liquefaction criteria (Figure 3). The figure shows that the number of cycles to reach 10% double amplitude strain is slightly higher than that to reach initial liquefaction. As the applied CSR decreases, the number of cycles to liquefaction increases and using either criterion would result in almost the same number of cycles. It should be noted that the results presented by Silver et al. (1976) compares 10% double amplitude axial strain to initial liquefaction and the results for 5% double amplitude strain should be even closer.

Ladd (1977) compared the number of cycles to reach initial liquefaction, 2.5%, 5%, 10% and 20% peak to peak strains (double amplitude) for different specimen preparation methods and different relative densities (Table 1). The results were consistent with those reported by Silver et al. (1976), and showed no significant difference between number of cycles to reach initial liquefaction and 10% double amplitude strain. Table 1 shows some of the results reported by Ladd (1977) where the specimens were prepared by vibration, moist vibration and moist tamping. For all preparation methods, the number of cycles to initial liquefaction and 5% double amplitude strain are almost identical.

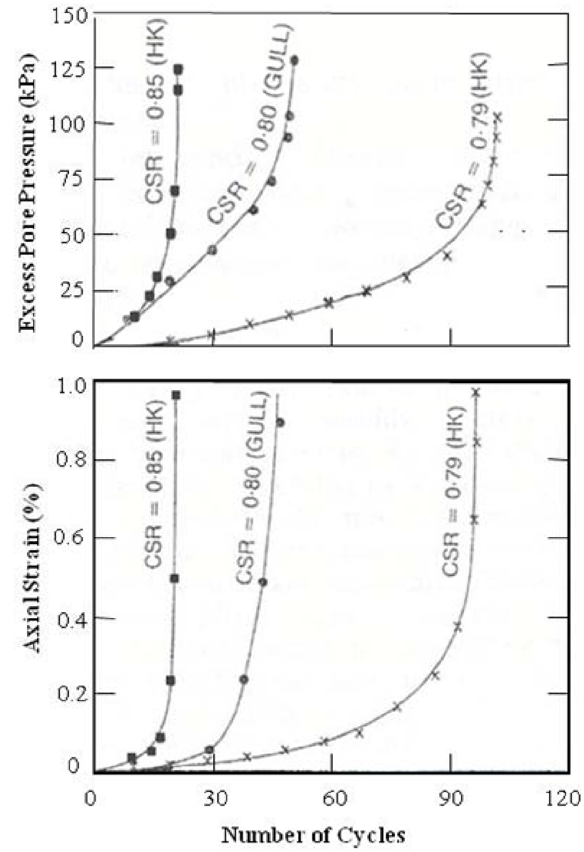

Figure 2. Overconsolidated (OCR=1.3) Ham river sand w/ kaolin and Gullfaks specimens (adapted from Georgiannou et al, 1991)

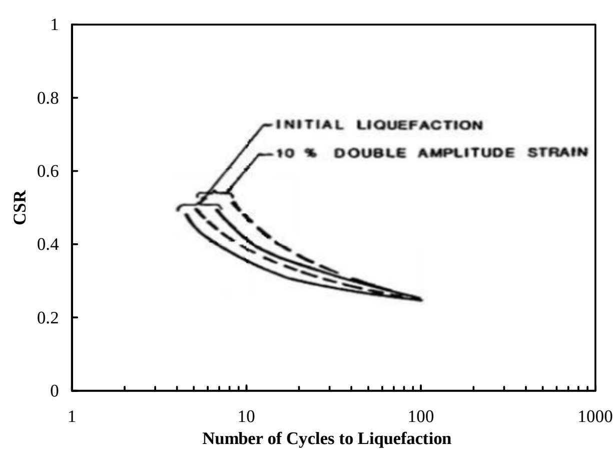

Figure 3. Cyclic resistance using initial liquefaction and 10% double amplitude strain as liquefaction criteria (adapted from Silver et al, 1976)

Based on all the data shown in this section, using initial liquefaction or 2.5%, 5% or even 10% double amplitude strain to define the number of the cycle at which liquefaction occurred would have little effect on the final results. The CSR versus number of cycles to liquefaction curve would shift slight to the left or right with minimal change in the value of CRR.

Table 1. Number of cycles to Initial liquefaction, 5% and 10% double amplitude strain (adapted from Ladd, 1977)

Relative Density (%)	Cyclic stress ratio, CSR	Number of cycles to		
		Initial Liquefaction	5% DA strain	10% DA strain
64.4	0.12	53	57	58
63.4	0.15	14	16	17
62.9	0.20	3	3.5	5
64.0	0.21	61	59	61
62.3	0.21	42	41	43

2.3 *Case where 5% double amplitude cannot be used*

Polito (1999) studied the effects of plastic and non plastic fines on the liquefaction of sandy soils. Polito concluded that, when preparing sandy soils and mixing them with high plasticity clays to achieve a plasticity index higher than 10 for the mixture, the traditional liquefaction criteria does not apply anymore. The soil experienced cyclic mobility but no flow liquefaction and the strain buildup was gradual with increasing number of loading cycles. The soil did not experience any significant increase in axial deformation at a given cycle and therefore, it would be harder to identify a specific number of cycles to liquefaction. Such soils would not have any significant reduction in strength and can be classified as non-liquefiable even if the strains reached 5% double amplitude.

3 LIQUEFACTION OF NON-TRADITIONAL SOILS

With devastating losses from liquefaction in the past century, there has been an increasing interest in liquefaction mitigation in the recent years; many researchers used cyclic triaxial testing for evaluating the effectiveness of the proposed mitigation methods. In general, this approach involves determining the cyclic resistance of a given soil (mostly sand) and then determining again the cyclic resistance of the same sand after it has been treated.

Maher et al. (1994) studied the cyclic undrained behavior and liquefaction potential of sand treated with chemical grouts and microfine cement while Gallagher and Mitchell (2002) studied the influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand. El Mohtar (2008) studied the undrained cyclic behavior of sand when replacing the pore fluid with a bentonite based thixotropic suspension. The use of these non-traditional materials in triaxial testing requires a deeper look at the criterion used for defining liquefaction. The results from the fore mentioned cases along with results from Polito (1999) on sands mixed with high percentages of high plasticity clays will be analyzed to determine if the trends discussed in the earlier section applies to these new geo-materials.

3.1 *Cases where 5% double amplitude strain worked*

Maher et al. (1994) examined the influence of grout type and curing time on the cyclic response of grouted sands. Figure 4 below was plotted from the data presented by Maher et al. (1994). The figure shows the results from specimens prepared at a relative density of 41% and tested after 14 days of curing. The results show a similar trend to that reported for sand where the number of cycles to liquefaction increases with decreasing cyclic stress ratio. Additionally, the results show insignificant differences between using initial liquefaction of 5% double amplitude strain as the liquefaction criteria.

Similar trends were found by El Mohtar (2008) when studying the undrained cyclic response of sand with thixotropic pore fluid. The tests were performed on loose Ottawa sand (relative density 30%-40%) with bentonite suspension in the pores corresponding to 3% and 5% by dry mass of sand. The pore pressure and axial strain generation during the cyclic loading followed similar trends to the clean sand (refer to section 2.1). The pore pressure build up starts at a fast rate for few cycles (mostly due to non uniformities in specimens) and then increases linearly with increasing number of cycles until few cycles from initial liquefaction. The axial strains are minimal up to this point after which the pore pressure generation accelerates till all the effective stress is lost. This is accompanied with a rapid increase in the axial strains. The specimens would go from initial liquefaction to 5% double amplitude strain in few cycles.

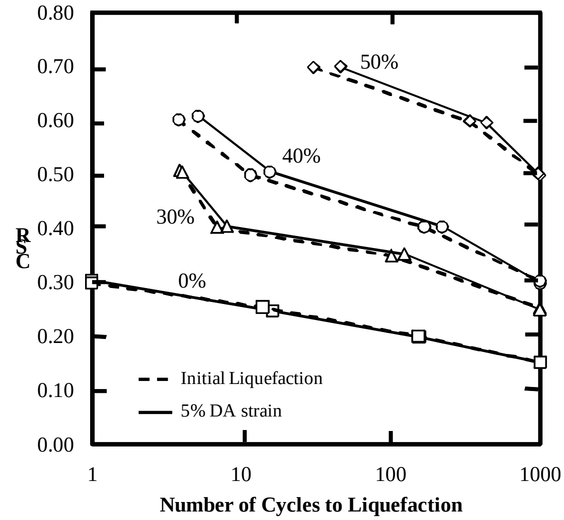

Figure 4. CSR versus number of cycles to liquefaction for sand with varying percentages of sodium silicate (Plotted from data in Maher et al. 1994)

3.2 *Cases where 5% double amplitude strain does not work*

Gallagher and Mitchell (2002) studied the cyclic behavior of sand with varying percentages of colloidal silica. The study was performed on Monterey # 0/30 sand with 0%, 5%, 10% and 20% colloidal silica by dry mass of sand at a relative density of 22%. Figure 5 is plotted from data published in Gallagher and Mitchell (2002) for sand and sand with 5% colloidal silica. The figure shows the number of cycles to reach 1%, 2% and 5% double amplitude strain for different CSR values.

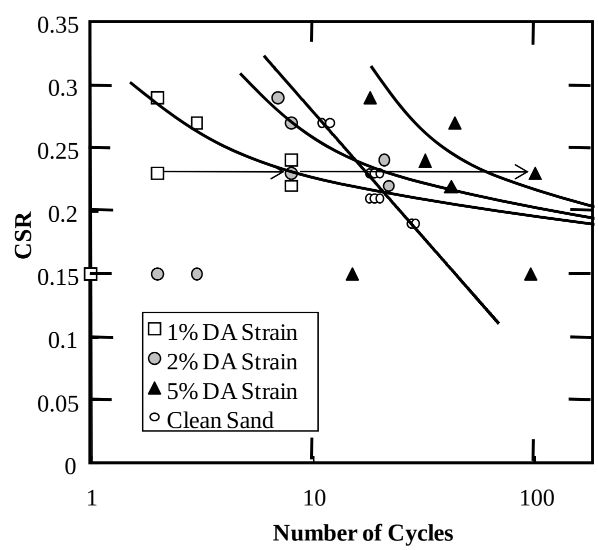

Figure 5. CSR versus number of cycles to 1, 2, and 5% double amplitude strain for sand with 5% colloidal silica (Plotted from Data in Gallagher and Mitchell, 2002)

The results for sand are combined since the number of cycles to reach 1%, 2% and 5% are almost identical. The initial liquefaction data was not available since the authors did not monitor the pore pressure generation. The results show a significant difference between the number of cycles to reach 1%, 2% and 5% double amplitude strain. For the specimen tested at CSR=0.23 (identified by the arrows in Figure 5), the axial strain reached 1% (2 cycles) and 2% (8 cycles) double amplitude in fewer cycles than clean sand (17 cycles) but took much more cycles to reach 5% double amplitude (100 cycles).

3.3 *Effect of liquefaction criteria on CRR*

To compare the effect of using different liquefaction criterion on the cyclic resistance, the results from El Mohtar (2008) and Gallagher and Mitchell (2004) are combined in Figure 6. It should be noted that Gallagher and Mitchell (2004) rightfully presented their data in terms of deformation resistance and not cyclic resistance. The CRR values in Figure 6 were calculated by the author. The sand with thixotropic pore fluid used by El Mohtar (2008) follow a similar trend to traditional soils whereas the colloidal silica sands showed a non-traditional cyclic response. The CRR was determined as CSR to generate liquefaction in 10 and 20 cycles; the CRR values for the treated sands were normalized by the CRR value for clean sand to eliminate the difference in the base sand used in the two studies and allow for a better comparison. The treated sand with traditional soil behavior shows no effect whether 1%, 2% or 5% double amplitude strains is used where as the CRR values increase by 40% to 50% for the non-traditional soils when using 5% as compared to 1% double amplitude strain.

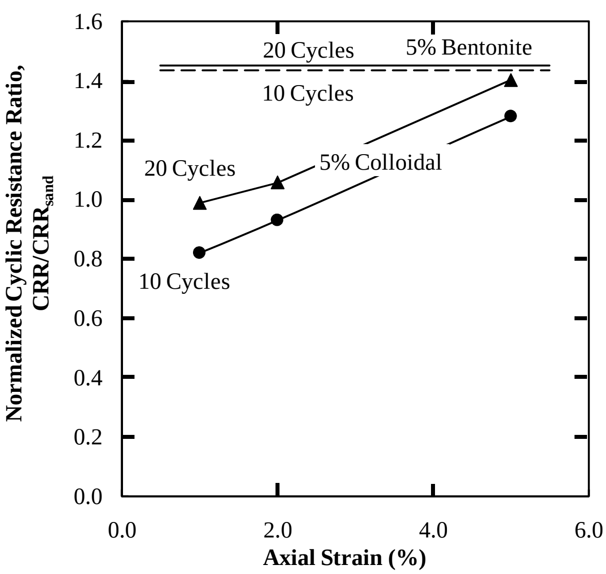

Figure 6. Normalized CRR values using 1%, 2% and 5% double amplitude axial strains liquefaction criterion (generated from data reported in Gallagher and Mitchell (2002) and El Mohtar (2008))

4 CONCLUSION

A compilation of data in the literature on the different criteria used to define liquefaction is presented in this paper. The results consistently show that for traditional soils, using initial liquefaction, 1%, 2%, 5% or even 10% double amplitude axial strain would result in very small changes in the measured cyclic resistance using cyclic triaxial testing in the laboratory.

On the other hand, for non-traditional soils where the soils have been treated with different grouts (bentonite suspensions, colloidal silica or sodium silicate), one should be more careful with selecting the liquefaction criterion. While some of these soils would still exhibit cyclic response similar to that of traditional soils, the response of others can be significantly different. A comparison between the results using different liquefaction criteria can be useful to better understand the cyclic behavior. While 5% double amplitude strains can be reached in high plasticity soils, such soils do not liquefy and therefore a distinction should be made between reaching 5% double amplitude strain and liquefaction for high plasticity soils.

Determining the liquefaction potential of a soil is very critical when planning and designing with natural insitu soils or evaluating a liquefaction mitigation technique. Therefore, using a suitable liquefaction criterion becomes critical especially in the case of non-traditional soils where the cyclic behavior of the soil can be different than that of natural soils. The cyclic resistance should be determined based on the design specifications of the application under consideration and an appropriate criterion needs to be specified. This criterion could be initial liquefaction or a specific double amplitude axial strain depending on the project tolerability to deformations. Using 5% double amplitude strains could result in over predicting the cyclic resistance of a treated soil when the soils exhibit cyclic mobility rather than flow liquefaction.

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