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# Liquefiable sand behavior under different applied consolidation pressures and cyclic stress

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ABSTRACT: Liquefaction is a phenomenon when saturated, cohesionless soil loses strength due to increasing pore water pressure; therefore, shear strength is reduced because of dynamic loading. After increasing the seismic activity in Zagros tectonic fold in recent years, it has become necessary to investigate the liquefaction possibility of the local Iraqi sand. The objective of the study is to determine a relation that can be used to estimate the liquefaction potential of this soil. Therefore, 49 cyclic triaxial tests have been conducted. Different consolidation pressures and cyclic stresses have been examined on loose sand using the cyclic stress control test method. The number of stress cycles required to cause liquefaction was determined. Moreover, shear and Young's moduli were calculated in addition to the damping ratio and shear wave velocity. It can be concluded that for a given consolidation pressure, the higher the cyclic stress, the lower the number of cycles required to cause liquefaction, and the lower the soil moduli and shear wave velocity. However, no effect of cyclic stress on the damping ratio has been noticed. On the other hand, for a given cyclic stress, an increase in consolidation pressure causes an increase in the number of cycles to cause liquefaction, as well as an increase in soil moduli and shear wave velocity. Damping ratio shows no variation with the consolidation pressure. An empirical relationship has been successfully derived to estimate the cyclic stress ratio (CSR) of loose saturated local Iraqi sand based on the number of stress cycles generated by an earthquake.

KEYWORDS: Liquefaction, cyclic triaxial test, cyclic stress ratio, soil moduli.

## 1 INTRODUCTION

The available data on the liquefaction behavior of local soils in Iraq is limited, despite increasing regional seismic activity in recent years. Several significant earthquakes have occurred across the country, with some reaching magnitudes of 7.3 on the Richter scale and a maximum acceleration of $a_{max} = 0.69g$. The present study aims to evaluate the liquefaction potential of Iraqi loose sand through a series of laboratory tests.

Structures may suffer damage due to ground settlement or lateral spreading of sloping ground as a result of earthquake load. The causes of these failures can be attributed to liquefaction phenomena. Loose sand is likely to lose its contact under the dynamic loading, which causes an increase in the pore water pressure of saturated sand during an earthquake. The result is a degradation in the effective confining stress of the soil, accompanied by a loss of stiffness and strength, which leads to deformations in the soil layer (Idriss & Boulanger, 2008).

For the cyclic triaxial test, the liquefaction potential depends on relative density ($D_r$), consolidation pressure ($\sigma'_c$) (which is the isotropic confining pressure applied to the specimen during consolidation), cyclic deviator stress ($\sigma_d$), and the number of load cycles to cause failure (N). Also, the liquefaction potential is affected by soil grain characteristics, drainage conditions, depositional environment, aging, cementation, and construction-induced loads (Seed & Lee, 1966). The applied cyclic shear stress ($\tau_{cyc}$) represents 0.65 of the maximum shear stresses induced by the maximum acceleration amplitude $a_{max}$ of an earthquake.

$$\tau_{cyc} = 0.65\, \sigma\, \frac{a_{max}}{g} \tag{1}$$

Cyclic stress ratio (CSR) is the induced cyclic shear stress $\tau_{cyc}$ acting on the horizontal planes divided by effective stress $\sigma'$.

$$CSR = \frac{\tau_{cyc}}{\sigma'} = 0.65 \left(\frac{\sigma}{\sigma'}\right) r_d \left(\frac{a_{max}}{g}\right) \tag{2}$$

Whereas: $r_d$ is a reduction factor for the depth, which can be obtained from Iwasaki (1986) as $r_d = 1 - 0.015z$. While $\sigma$ and $\sigma'$ are the total and effective stress at the depth of the soil element, respectively.

For an isotropic consolidated cyclic triaxial test, CSR is the ratio of the maximum cyclic deviator stress ($\sigma_d$) to the isotropic consolidation pressure ($\sigma'_c$)

$$CSR = \frac{\sigma_d}{2\sigma'_c} \tag{3}$$

For sand with specific soil properties, CSR is a function of the number of stress cycles that cause initial liquefaction (N). The appropriate number of significant stress cycles (N) will rely on the duration of ground shaking and the magnitude of the earthquake. The variation of this relation was developed by Idriss (1999), as shown in Figure 1.

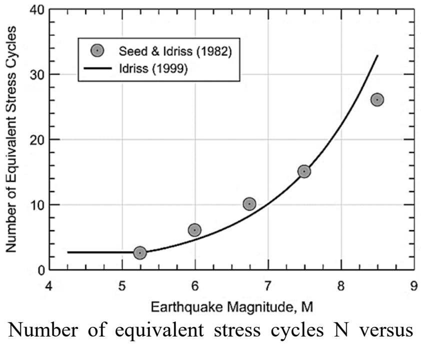


Figure 1. Number of equivalent stress cycles N versus earthquake magnitude (after Idriss, 1999).

The cyclic stress ratio (CSR) and number of cycles (N) significantly affect the excess pore water pressure ($\Delta u$) and the associated dynamic soil properties; the shear modulus (G) measured from each cycle with accumulated shear strain shows a conventional degradation pattern with the increase in shear strain corresponding to CSR, while the damping ratio (D), which is a factor of dynamic energy loss per cycle due to internal friction and pore pressure dissipation, shows a non-conventional degradation pattern beyond a shear strain (Kumar et al., 2015).

For loose saturated clean sand, the number of applied strain cycles to cause initial liquefaction in strain-controlled tests decreased sharply as the applied cyclic strain increased to an extent of $\varepsilon$=1.0%, after this value, there is no effect of the applied cyclic strain amplitude on the number of cycles to cause initial liquefaction (Al-Omari et al., 2018).

## 2 EXPERIMENTAL WORK

The soil used in the tests was a saturated clean loose sand (i.e., fine content ≤5.0%). The properties of the used sand are summarized in Table 1. Specimens with a 38 mm diameter and 76 mm height were prepared for the triaxial tests in a dry state and subsequently saturated. In this study 49 specimens were tested under a set of (15, 25, 30, 50, 75, 100, and 125) kN/m$^2$ consolidation pressures ($\sigma'_c$) The specimen was then tested by applying a set of cyclic deviator stress ($\sigma_d$) of (20, 30, 40, 50, 60, 80, and 100) kN/m$^2$, using a cyclic frequency of $f$=2.0 Hz.

Table 1. Properties of the used sand.

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Relative density | $D_r$ | 33 | % |
| Max. unit weight | $\gamma_{max}$ | 17.72 | kN/m$^3$ |
| Min. unit weight | $\gamma_{min}$ | 14.80 | kN/m$^3$ |
| Dry unit weight | $\gamma_d$ | 15.65 | kN/m$^3$ |
| Total unit weight | $\gamma_t$ | 19.55 | kN/m$^3$ |
| Water content | $w_c$ | 25 | % |
| Specific gravity | $G_s$ | 2.65 | - |
| Max. void ratio | $e_{max}$ | 0.757 | - |
| Min. void ratio | $e_{min}$ | 0.467 | - |
| Void ratio | $e$ | 0.661 | - |
| Fine content | - | 4.0 | % |
| Effective size | $D_{10}$ | 0.162 | mm |
| Mean size | $D_{50}$ | 0.394 | mm |
| Coefficient of Permeability | $k$ | $1.21\times10^{-2}$ | cm/sec |
| Friction angle | $\varphi$ | 34 | degree |
| Cohesion | $c$ | 0 | kN/m$^2$ |
| Soil classification (USCS) | | Poorly-graded sand, SP | |

## 3 RESULTS AND DISCUSSION

The cyclic stress control triaxial tests have been carried out according to ASTM-D5311 (2013) and ASTM-D3999 (2011). The test results present the cyclic deviator stress ($\sigma_d$) and the excess pore water pressure ratio ($r_u$), which is the relation of the excess pore water pressure ($\Delta$u) to the consolidation pressure ($r_u = \Delta u/\sigma'_c$) along with the number of stress cycles (N), which is considered to be either the number of stress cycles that caused 20% strain or the number of stress cycles that caused initial liquefaction, whichever occurs first. The excess pore water pressure ratio indicates the liquefaction potential, as initial (fully) liquefaction soil has $r_u$=1.0, which means the soil has totally lost its shear strength, i.e., $\Delta u = \sigma'$ .

Also, this study presents the determination of Young's modulus (E), shear modulus (G), shear wave velocity ($V_s$), and damping ratio (D) determined from the hysteresis loop.

The resulting number of cycles for different consolidation pressures and cyclic deviator stresses are listed in Table 2.

Table 2. Resulted number of stress cycles (N) for different consolidation pressures ($\sigma'_c$) and cyclic deviator stresses ($\sigma_d$).

| cyclic stresses $\sigma_d$ (kN/m$^2$) | Consolidation pressures ($\sigma'_c$), (kN/m$^2$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 15 | 25 | 30 | 50 | 75 | 100 | 125 |
| 20 | 3 | 10 | 17 | + | + | + | + |
| 30 | 3 | 5 | 7 | 22 | + | + | + |
| 40 | 2 | 4 | 3 | 8 | 130 | 190 | 314 |
| 50 | 1 | 4 | 3 | 6 | 30 | 135 | 279 |
| 60 | 1 | 2 | 2 | 4 | 6 | 69 | 97 |
| 80 | – | – | – | – | 2 | 5 | 7 |
| 100 | – | – | – | – | – | – | 3 |

+ Did not reach the failure; due to a relatively low cyclic stress with a high consolidation pressure.

– Collapsed before the end of the first stress cycle; due to a relatively high stress with a low/medium consolidation pressure.

Figure 2 summarizes the variation for the resulting number of cycles versus consolidation pressures for different applied cyclic stresses. It can be concluded that the number of stress cycles increases as the consolidation pressure increases for all applied cyclic stresses. On the contrary, the number of stress cycles decreases as the applied cyclic stress increases.

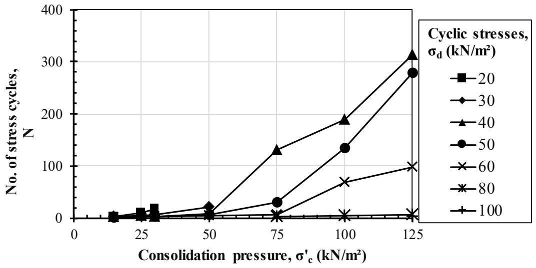


Figure 2. The variation of the number of cycles (N) results with consolidation pressure ($\sigma'_c$) for different applied cyclic stresses ($\sigma_d$).

The excess pore water pressure ratio ($r_u$) increased sharply after a few cycles and remained constant at the peak as the stress cycled. In many tests, the excess pore water pressure ratio showed a slight decrement at the end of the test duration. Figure 3 shows the plot of the excess pore water pressure ratio with consolidation pressure for different cyclic stresses. It shows that as the consolidation pressure increases, the $r_u$ value decreases. At the same time, the cyclic stress did not present any indication for the $r_u$ value. It is revealed that approximately 53% of the tested specimens failed in the initial liquefaction criterion, while the others failed in the 20% strain criterion.

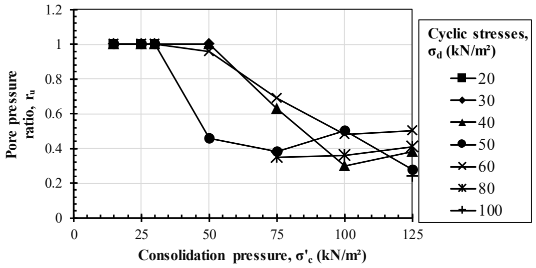
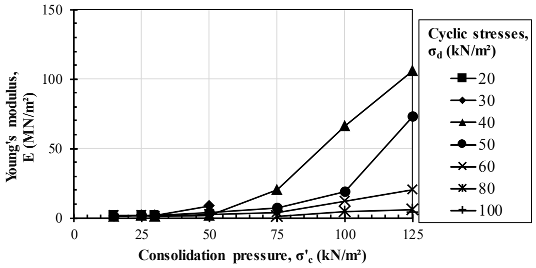
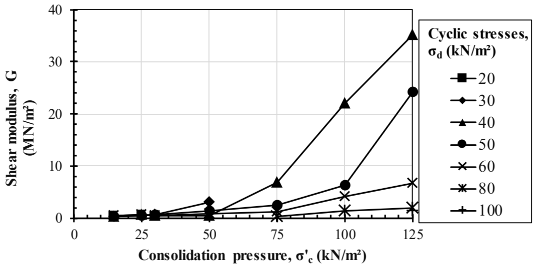


Figure 3. The variation of the excess pore water pressure ratio ($r_u$) with consolidation pressure ($\sigma'_c$) for different cyclic stresses ($\sigma_d$).

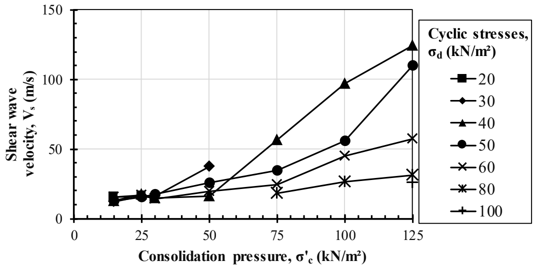
The variation of sand moduli (E and G), shear wave velocity ($V_s$), and damping ratio (D) with consolidation pressure ($\sigma'_c$) for different applied cyclic deviator stresses ($\sigma_d$) of sand is summarized in Figure 4. It is obvious that the average sand moduli and the shear wave velocity increase as the consolidation pressure increases; this increase occurs gradually before $\sigma'_c$ = 50 kN/m$^2$ and sharply after this value. The average sand moduli and the shear wave velocity reduce as the applied cyclic deviator stress increases. It can be seen that there is no significant effect of the consolidation pressure and the cyclic deviator stress on the damping ratio of the used loose sand.



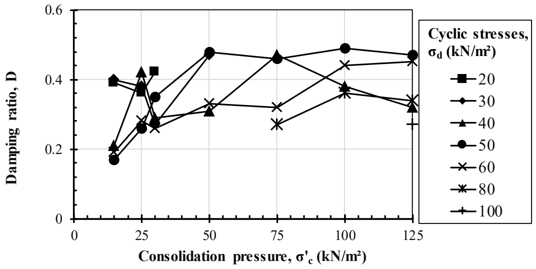
(a) Young’s modulus (E)



(b) Shear modulus (G)



(c) Shear wave velocity ($V_s$)



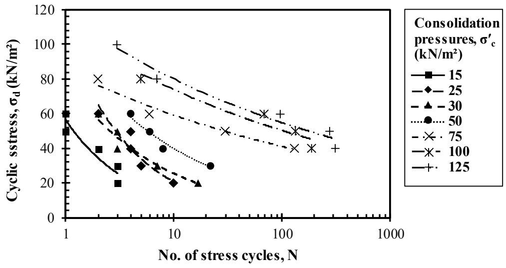
(d) Damping ratio (D)

Figure 4. The variation of soil moduli (E and G), shear wave velocity ($V_s$), and damping ratio (D) with consolidation pressure ($\sigma'_c$) for different applied cyclic stresses ($\sigma_d$).

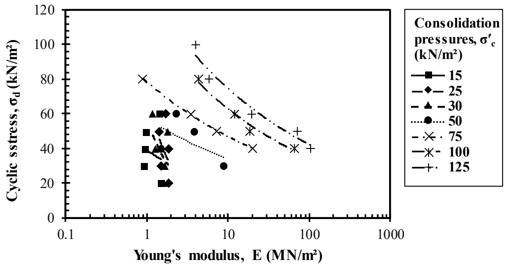
### 3.1 *Influence of cyclic stress ($\sigma_d$)*

The influence of the cyclic deviator stress on the number of cycles, Young’s modulus, shear modulus, and shear wave velocity for different consolidation pressures is shown in Figure 5. It is found that, for a given consolidation pressure, the higher the cyclic deviator stress, the lower the number of required cycles; previous studies by Lee & Seed (1967) have demonstrated the same finding.

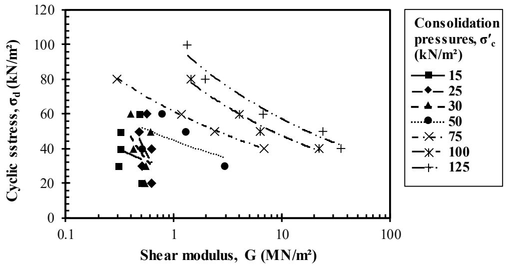
Additionally, it can be observed that the higher the cyclic deviator stress, the lower the soil moduli and shear wave velocity; however, there is no effect of cyclic deviator stress on the damping ratio. It is worth noting that the cyclic deviator stress is a function of the maximum earthquake acceleration $a_{max}$ expected in the field.



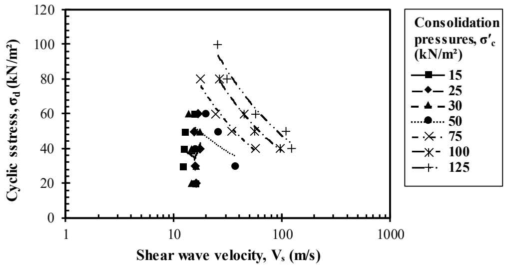
(a) Number of cycles (N)



(b) Young’s modulus (E)



(c) Shear modulus (G)



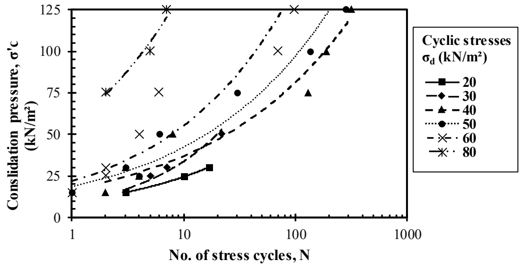
(d) Shear wave velocity ($V_s$)

Figure 5. The effect of cyclic stress ($\sigma_d$) on number of cycles (N), soil moduli (E and G), and shear wave velocity ($V_s$) for different consolidation pressures ($\sigma'_c$).

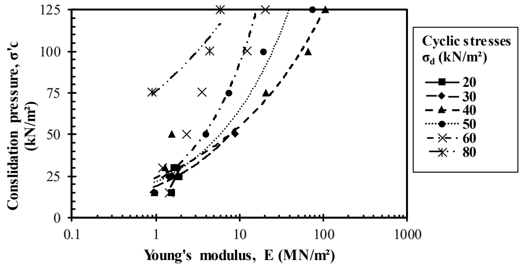
### 3.2 *Influence of consolidation pressure ($\sigma'_c$)*

The influence of the consolidation pressure on the number of cycles, soil moduli, and shear wave velocity for different cyclic deviator stresses is shown in Figure 6. It is concluded that, for a given cyclic deviator stress, as the consolidation pressure increases, the number of cycles increases. This conclusion seems to be consistent with the findings of Lee & Seed (1967). Moreover, the sand moduli and shear wave velocity increase as the consolidation pressure increases, whereas the damping ratio shows no variation with the consolidation pressure.

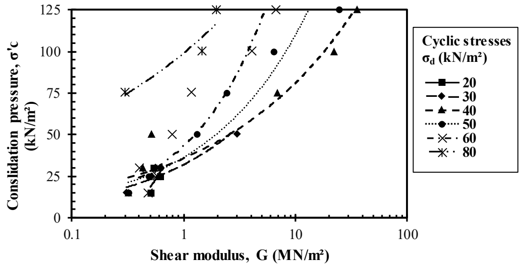
It has been observed that the initial liquefaction did not occur at a consolidation pressure of $\sigma'_c$= 75 kN/m² or higher, which corresponds to an approximate depth of ≥ 7.7 meters. Higher consolidation pressures can result from deeper soil layers and/or the application of surface surcharges. This observation is consistent with the findings of Seed and Idriss (1971).



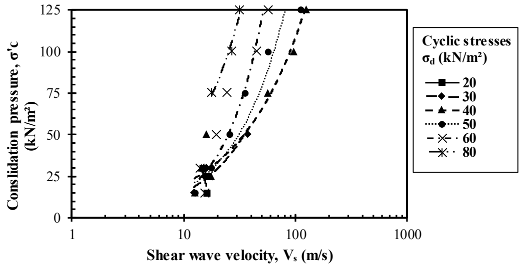
(a) Number of cycles (N)



(b) Young's modulus (E)



(c) Shear modulus (G)



(d) Shear wave velocity ($V_s$)

Figure 6. The effect of consolidation pressure ($\sigma'_c$) on the number of cycles, soil moduli, and shear wave velocity for different cyclic stress.

### 3.3 *Cyclic stress ratio (CSR)*

The results can be summarized and simplified by a single relationship of the cyclic stress ratio (CSR), which is determined using Equation (3) and then plotted versus the number of cycles (N) on a log-log scale as presented in Figure 7. An empirical equation can be derived to describe the relationship between CSR and the number of cycles to cause liquefaction (N) for the used loose sand (Karbala, Iraq), generally expressed as:

$$CSR = 1.07(N)^{-0.34} \tag{4}$$

This relationship can be employed to evaluate the liquefaction resistance of sandy soil that has similar properties, as the number of stress cycles (N) associated with an expected earthquake can be correlated with its magnitude (see Figure 1), which is typically determined based on the seismic history of a specific region. Finally, the liquefaction potential can be determined by comparing the resistance CSR from Equation (4) to CSR induced by an earthquake from the Equation (2).

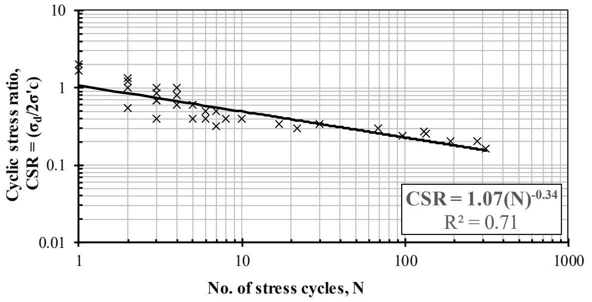


Figure 7. The variation of the resistance cyclic stress ratio (CSR) with the number of stress cycles (N) for loose saturated sand.

## 4 CONCLUSION

The cyclic triaxial test presents a reliable method for investigating soil behavior under dynamic stresses and studying the liquefaction potential of sand. This study focuses on the behavior of saturated clean loose sand (local sand from Karbala, Iraq) under cyclic stress by examining the generation of excess pore water pressure that causes liquefaction, as well as the soil moduli, shear wave velocity, and damping ratio under various consolidation pressures and applied cyclic stresses. It can be concluded that for a given consolidation pressure, as cyclic deviator stress increases, the number of cycles required to cause liquefaction, soil moduli, and shear wave velocity decrease; however, the damping ratio has not been affected by the cyclic stress. On the other hand, for a given cyclic deviator stress, an increase in consolidation pressure causes an increase in the number of cycles to cause liquefaction, soil moduli, and shear wave velocity. Similarly, the damping ratio also shows no variation with the consolidation pressure. An empirical relationship has been derived to estimate the cyclic stress ratio (CSR) of loose saturated sand based on the number of stress cycles generated by an earthquake, which can be used to assess the liquefaction potential of sand.

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