Effects of Relative Density and Effective Confining Pressure on Liquefaction Resistance of Sands

Effets de la densité relative et pression de confinement effective sur la résistance à la liquéfaction des sables

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ABSTRACT: Soil liquefaction during earthquake is deemed to be responsible for the failure of many infrastructures. This research aimed to examine the effects of relative density and initial effective confining pressure on liquefaction resistance of selected saturated sands. Series of laboratory undrained cyclic triaxial tests were carried out on two different sands at different relative densities and effective confining pressures. Results of the cyclic triaxial tests revealed that Cyclic Stress Ratio (CSR) that serves as an index for liquefaction resistance, at relative densities of 30%, 50%, and 70% are 0.15, 0.21, and 0.24 respectively. An increase in relative density results in an increase in CSR thereby making the soil more resistant against liquefaction. For a constant relative density of 55%, an increase in initial effective confining pressure from 50 kPa to 100 kPa caused CSR to decrease from 0.30 to 0.12. It is clear that soils are more resistant against liquefaction at low effective confining stresses than at relatively higher effective confining stresses.

RÉSUMÉ: La liquéfaction des sols pendant les tremblements de terre est réputée être responsable de l'échec de nombreuses infrastructures. Cette étude visait à examiner les effets de la densité relative et de la pression de confinement effective initiale sur la résistance à la liquéfaction de sables saturés sélectionnés. Des séries de tests triaxiaux cycliques non entraînés en laboratoire ont été réalisées sur des sables de deux sables différents à différentes densités relatives et pressions de confinement efficaces. Les résultats des essais cycliques triaxiaux révèlent que le rapport de contrainte cyclique (CSR) qui sert d'indice de résistance à la liquéfaction, à des densités relatives de 30%, 50% et 70% est respectivement de 0,15, 0,21 et 0,24. Une augmentation de la densité relative entraîne une augmentation de la CSR, ce qui rend le sol plus résistant contre la liquéfaction. Pour une densité relative constante de 55%, une augmentation de la pression de confinement effective initiale de 50 kPa à 100 kPa a conduit la CSR à diminuer de 0,30 à 0,12. Il est clair que les sols sont plus résistants contre la liquéfaction à des contraintes de confinement efficaces faibles qu'à des contraintes de confinement efficaces relativement plus élevées.

KEYWORDS: saturated sand, relative density, effective confining pressure, cyclic triaxial test and liquefaction resistance.

1 INTRODUCTION

The first widespread observations of damage attributed to soil liquefaction were made in the 1964 Niigata and Alaska earthquakes. Spectacular examples of liquefaction induced failure have also been widely observed during most moderate to large size earthquakes around the world. Since 1964 Alaska and Niigata earthquakes, liquefaction has been studied extensively by many investigators and substantial advances have been made in both understanding and practice with regard to assessment and mitigation of liquefaction induced hazards. However, major advances have occurred in the field of seismically induced soil liquefaction, catastrophic failures in recent earthquakes have provided a sobering reminder that liquefaction of soils as a result of earthquake poses a major threat to the safety of infrastructures. There is no reported case history of seismically induced soil liquefaction in Bangladesh, but location of this country in world seismic map, geologic formation and frequent earthquakes in and around the country remind the great danger of seismically induces soil liquefaction. This research aimed to examine the effects of relative density and initial effective confining pressure on liquefaction resistance of saturated sands using laboratory cyclic triaxial test.

2 LITERATURE REVIEW

The effects of relative density and initial effective confining pressure on liquefaction resistance of saturated sands undercyclic loading condition have been extensively investigated by many researchers in the laboratory cyclic triaxial tests. The outcome of these studies generally agreed that, the resistance to liquefaction of sands tends to increase with an increase in relative density and decrease with increase in effective confining pressure. Extensive laboratory investigations on Toyoura sand revealed that, up to a relative density of 70%, liquefaction resistance tends to increase linearly with the relative density, but for the density in excess of 70%, the cyclic strength goes up sharply (Tatsuoka et al. 1986). Undrained cyclic triaxial tests results on clean Ottawa sand (Carraro et al. 2003) and white natural quartz sand (Stamatopoulos 2010) have also illustrated that,the resistance to liquefaction increases as the relative density increases. Other laboratory studies (Liu and Xu 2013, Belkhatir et al. 2010, Vaid and Sivathayalan 2000) have equally provided strong evidence that the liquefaction resistance of sand increases with increase in relative density.

Laboratory research on rounded Ottawa sand and angular tailing sand illustrated that, substantial decrease in resistance to liquefaction occurred for both sands with increase in effective confining pressure in the range of 200 kPa to 2500 kPa (Vaid et al. 1985). It was apparent that, the resistance to liquefaction for both sands at all level of confining pressure tends to converge around a relative density of 50-55%. This implies that, the influence of confining pressure on reduction of resistance against liquefaction may be significant only for densities larger than a certain minimum. In addition, laboratory test results confirmed that, initial effective confining stress does not have any influence on the resistance to liquefaction at loose density (Dr = 19%) state (Thomas 1992). But at high relative densities of 40% and 59%, resistance to liquefaction decrease with increase in initial effective confining stress, height decrease being associated with the densest state. So, it is obvious that resistance to liquefaction of sand decrease with increase in initial effective confining pressure and this effect is more pronounced as the sand specimens become denser.

A significant amount of research has been conducted in the field of soil liquefaction around the world, but there are very limited numbers of laboratory research (Hoque et al. 2013, Karim and Alam, 2014) have been undertaken to evaluate liquefaction resistance of local soils. A study was therefore carried out to examine the liquefaction resistance of locally available soils.

3 EXPERIMENTAL INVESTIGATIONS

3.1 *Test Materials*

For this research, two different types of poorly graded sands were collected; one from subsurface at Rooppur, Pabna and another from the bed of Piyain river at Jaflong, Sylhet. Index properties of the tested sands are given in Table 1. Both sands are grey in color and composed of subrounded particles in shape. According to Unified Soil Classification System these sands are classified as poorly graded sands with silt (SP-SM).

Table 1.Index properties of the sands

Index Properties	*Rooppur sand*	*Piyain river sand*
Specific gravity	2.66	2.65
Fineness Modulus	0.5	1
Mean grain size, D_{50} (mm)	0.15	0.21
Fines (%)	13	11.7
Minimum density (kN/m^3)	13.15	12.15
Maximum density (kN/m^3)	17.95	16.7

Particle size distribution curves for Rooppur sand and Piya in river sand are presented in Figure1. From these curves it can be observed that, both sand samples contain appreci able amount of fine particles.

3 .2 *Specimen Preparation*

Soil specimens of size 142 mm in height and 71 mm in diameter were prepared using wet tamping technique. After taking required amount of dry sand in a container, a measured amount of de-aired water was added to the sand to bring the moisture content approximately to 10 percent by weight of dry sand. The sand and water was then mixed thoroughly and the container was sealed and kept for half an hour to insure uniform water content distribution throughout the sand. The moist sand was then placed into the mold in six separate layers of equal mass and thickness. The layer mass was determined from the target relative density of the specimen. Each layer was compacted using a manually operated aluminum hammer of diameter 35.5 mm, weight of 1000 gm and equipped to provide a free fall height of 152.4 mm. The numbers of blows required on each layer to achieve target relative density was determined by several trials.

A total of 26 soil specimens were prepared using Rooppur sand at three different relative densities of 30%, 50% and 70% and tested at a constant initial effective stress of 100 kPa. Using Piyain river sand, a total of 11 specimens were prepared at a constant relative density of 55% and tested at two different effective confining pressures of 50 kPa and 100 kPa. In both test series, cyclic stress ratio was kept in the range of 0.10 to 0.40.

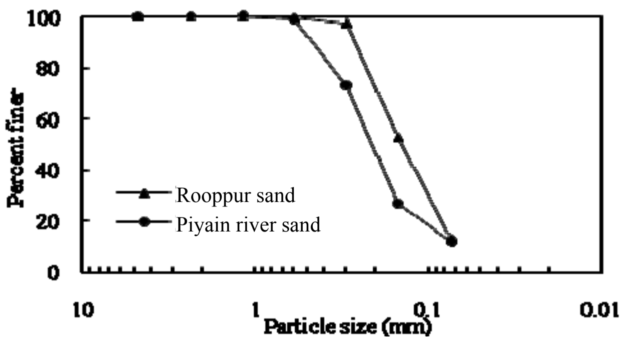

Figure 1.Particle size distribution curves

3.3 *Cyclic Triaxial Test*

The prepared specimen was sealed in a water tight rubber membrane with O-ring and confined in a triaxial chamber where it was subjected to a confining pressure of 20 kPa. In order to improve initial saturation of the specimen, carbon dioxide (CO_2) was allowed to flow through the specimen at a low pressure (less than 20 kPa) in order to replace the air in the specimen pores. This was done because CO_2 has a much higher solubility in water than air, allowing a higher degree of saturation to be reached at lower backpressure.After 30 minutes, the flow of CO_2 was stopped and a tank of de-aired water was attached to the drainage line on the bottom platen. The de-aired water was then percolated from the bottom trough the top of the specimen by gravitational force in order to increase the degree of saturation and percolation was continued until all CO_2 from specimen's pores has been replaced. Once the desired volume of de-aired water had flowed through the specimen, the drainage valves on the cell were closed and the de-aired water line removed. The drainage line is then connected to the pore pressure line.The specimen was then saturated with de-aired water using backpressure saturation. The backpressure was increased gradually while maintaining the effective confining pressure at 10 kPa. This process was continued until the Pore Pressure Parameter B value exceeded 0.95. Following saturation, the sand specimen was isotropically consolidated to desired effective stress.At the end of the consolidation it was ensured that the pore pressure parameter B remains unchanged.

Undrained cyclic loading was then applied on the specimen using stress controlled method. The magnitude of cyclic load to be applied on the soil specimens for the desired cyclic stress ratio was automatically calculated by operating software based on the initial input parameters. In the entire test program, a harmonic cyclic load was applied using sine wave with a frequency of 1 Hz. The maximum peak to peak axial strain of

10% was recorded. The numbers of loading cycles was limited to 200 cycles with a specified data recording speed of 100 data points per cycle to give the adequate resolution to measure sample response in terms of load, deformation and pore water pressure. During the whole test procedure enormous amount of data were recorded such as axial deformation, cell pressure, cyclic load, and sample pore water pressure, normal stress, and shear stress using the cyclic triaxial software.

3.4 *Data calculation*

As the deviator stress cycles between compression and extension, pore water pressures in the specimen builds up steadily, effective stress decreases, and the specimen undergoes axial deformation. Excess pore water pressure builds up steadily with the applied loading cycles, and eventually approaches a value equal to the initially applied confining pressure, thereby producing an axial deformation of about 5% in double amplitude. Such a state has been referred to as initial liquefaction or simply liquefaction. Typical undrained response of a specimen in the form of deviator stress, axial deformation and induced excess pore water pressure with number of loading cycles obtained at cyclic stress ratio of 0.22 and initial effective confining stress of 100 kPa at relative density of 50% are given in Figure 2.

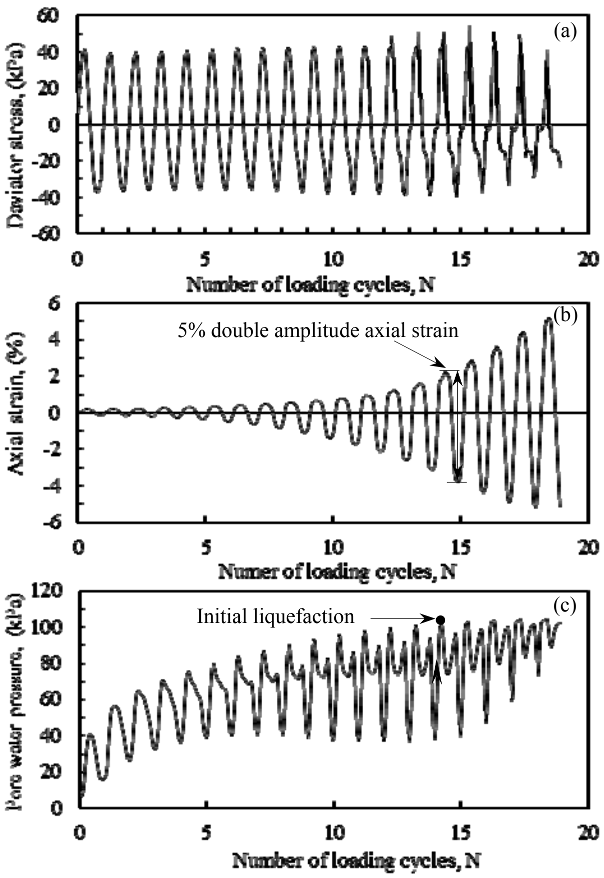

Figure 2. Typical undrained response of a specimen (a) deviator stress, (b) axial strain, and (c) induced excess pore water pressure with number of loading cycles

It can be seen from Figure 2 that, under constant amplitude of cyclic deviator stress applications the excess pore water pressure increases gradually and reached the value just equal to the initial applied effective confining pressure. At the beginning of the test development excess pore water pressure in the specimen is relatively slow and the axial deformation in the specimens is small. As the pore water pressure start to increase rapidly, axial deformation also speeds up. When excess water pressure reached just equal to initial effective confining pressure, it take only few cycles to reach 5% double amplitude axial strain, which is defined as initial liquefaction.

For each cyclic stress ratio, number of cycles required to reach 5% double amplitude axial strain are recorded. Such data from several tests are then combined and plotted as cyclic stress ratio versus number of cycles required to reach initial liquefaction, which is commonly known as liquefaction resistance or cyclic triaxial test strength curve. From cyclic strength curve, the liquefaction resistance of the specimen is specified in terms of magnitude of cyclic stress ratio (CSR) required to reach 5% double amplitude axial strain in 20 cycles of uniform load application.

4 RESULTS AND DISCUSSION

4.1 *Effects of relative density*

Cyclic shear strength curves constructed based on 26 undrained cyclic triaxial tests on Rooppur sand at three different relative densities are shown in Figure 3 and the assessed liquefaction resistance corresponding to relative densities of 30%, 50% and 70% are 0.15, 0.21 and 0.24 respectively. It can clearly be seen from Figure 3 that, the increase in relative density results in increase in liquefaction resistance. Controlling initial test conditions and test procedures identical it was noticed that, the change in relative density from 30% to 50% results in 40% increase in liquefaction resistance, while change in relative density from 30% to 70% results in 60 % increase in liquefaction resistance. It is also apparent that the cyclic strength curve corresponding to each relative density shifts consistently to the right along x-axis as the relative density becomes higher. Which implies that, the number of cycles required to occur initial liquefaction increase with increase in relative density. So, an increase in relative density causes significant increase in resistance against liquefaction, thereby making soils less susceptible to liquefaction.

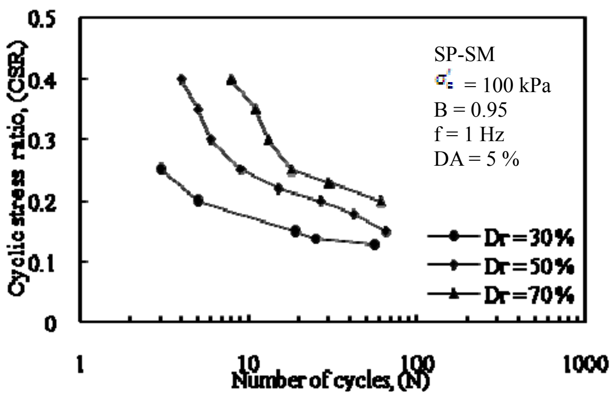

Figure 3. Cyclic shear strength curves for relative density of 30%, 50% and 70% at initial effective confining pressure of 100 kPa

4.2 *Effect of Confining Pressure*

Liquefaction resistance curves generated based on a total of 11undrained cyclic triaxial tests on Piyain river sand at two different initial effective confining pressure of 50 kPa and 100 kPa at a constant relative density of 55% are depict in Figure 4. It can be clearly seen from Figure 4 that, increase in initial effective confining pressure results dramatic reduction of resistance against liquefaction. Remaining initial test conditions and test procedures identical it was observed that, an increase in initial effective confining pressure from 50 kPa to 100 kPa caused liquefaction resistance to decrease from 0.30 to 0.12. Hence, soils at high effective confining stress are more susceptible to liquefaction than those at low effective confining pressure.

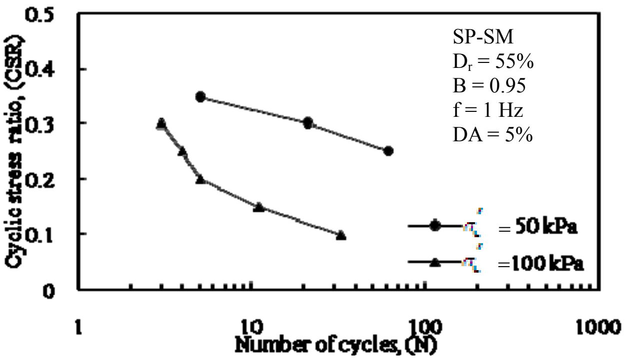

Figure 4. Cyclic shear strength curves for initial effective confining pressure of 50 kPa and 100 kPa at relative density of 55%

5 CONCLUSIONS

Series of laboratory undrained cyclic triaxial tests were carried out on two different sands at different relative densities and effective confining pressures in order to examine the effects of relative density and initial effective confining pressure on liquefaction resistance of saturated sands. Two local sands were used in this investigation. Laboratory tests results illustrated that, relative density and initial effective confining pressure has great influence on liquefaction resistance. Increase in relative density results significant increase in resistance against liquefaction. The rate of increase is almost linear with relative density. On the other hand, resistance against liquefaction decreased dramatically as the initial effective confining pressure increased. As the initial effective confining pressure was doubled from 50 kPa to 100 kPa, the value of CSR decreased to about one-third from the value at initial confining pressure of 50 kPa. The results obtained in this research are reasonably in agreement with the results reported in literature considering initial test conditions and test procedures.

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